UNIVERSITY OF ALBERTA

EVALUATION OF OPERATIONAL PARAMETERS ON YARD WASTE COMPOSTING PERFORMANCE

BY

JOSEPH HAROLD FEEHAN ©

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE**.

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Dedicated to my wife Cathy Lyn, who I love very much and to our wonderful son David Daniel born on May 31 1994.

Abstract

Urban centres in Canada develop a large amount of yard waste and most of the waste is sent to landfills for disposal, but composting is now becoming a more favourable waste management option. Composting increases the active life of the existing landfills and develops a useful product for horticultural and agricultural purposes. In Canada, climatic conditions reduce the time available for active composting, thus placing resistrictions on land use and delaying the possible sale and use of the compost.

The goal of this research was to identify practical means to optimize the process of composting yard waste materials under field and local climatic conditions and hence reduce the time required to produce a mature and stable compost product. The specific objectives of the study were: to systematically evaluate the influence of key operational parameters on the decompostion rate and to identify a practical indicator of compost stability and maturity.

A factorial experimental design approach was selected to evaluate the influence of the operational variables, C:N ratio, moisture content, and porosity. Two large experimental windrows approximately 61 m long, 4.27 m wide and 1.83m high each containing 8 different pile sections were built according to the specifications of the experimental design.

The factorial results using the % decrease in the total organic carbon as the response variable found none of the effects to be significant at the 5 % significance level. The 90 % confidence intervals, half normal plots and effect rankings for the full composting period provided indications the 13, (C:N ratio-Porosity) 23 (MC-Porosity) and the 123 (C:N ratio-MC-Porosity) interactions marginally influenced the decomposition rate of the organic materials. The decompositional rates for the parameters % C and total organic carbon (TOC) over time were found to follow either first or second order kinetics. A possible explanation for the second order results is the rate of hydrolysis of the substrate may depend

upon A_v (related to substrate concentration) and microbial concentration which is a function of the available substrate concentration through the yield coefficient.

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TABLE OF CONTENTS

1.0 INTRODUCTION 1
1.1 Problem Statement 1
1.2 Thesis Objectives 2
1.3 Thesis Structure 2
1.4 Scope and Limitations 3
2.0 THEORY DEVELOPMENT 5
2.1 Introduction 5
2.2 Composting Systems 5
2.3 Chemical Composition of Organic Materials 7
2.4 Microbiology and Process Principles 10
2.4.1 Microbiology 10
2.4.2 Composting Stages 12
2.4.3 Process Steps 13
2.4.4 Section Review 14
2.5 Rate Limiting Factors 15
2.5.1 Nutrient Concentration and Availability 15
2.5.2 Moisture Content 19
2.5.3 Aeration- Oxygen Concentration 20
2.5.4 Temperature 23
2.5.5 pH 24
2.5.6 Section Summary 25
2.6 Compost Maturity Parameters 25
2.6.1 Plant Bioassays 27
2.6.2 Microbial Bioassays 28
2.6.3 Chemical Analyses 31
2.6.3.1 Solid Phase 31
2.6.3.2 Degree of Humification 33
2.6.3.3 Water Extracts 34
2.6.4 Physical Tests and Spectroscopy 37
2.6.5 Maturity Selection Criteria 38
2.6.6 Section Review 39
2.7 Decomposition Models 41
2.7.1 First Order Models - Michaelis - Menten Type 42
2.7.2 First Order Model - Change in Compost Mass 48

2.7.3 Other Composting Kinetics Studies 52
2.7.4 Decomposition of Plant Residues 53
2.8 Section Summary 55
2.9 Summary and Hypotheses 56
3.0 EXPERIMENTAL DESIGN 59
3.1 Factorial Design 59
3.1.1 Operational Variables and Experimental Levels 60
3.1.2 Response Variables 61
3.1.3 Design Matrix 62
3.1.4 Composting Process and Pile Descriptions 64
3.1.5 Operational Activities 67
3.2 Method and Materials 71
3.2.1 Windrow Feedstock Materials 71
3.2.2 Field Data Collection 71
3.2.2.1 Temperature and Oxygen Measurements 71
3.2.2.2 Bulk Density Measurements 73
3.2.2.3 Sampling Methods and Procedures 73
3.2.3 Laboratory Analyses - Solid Samples 76
3.2.3.1 Percent Moisture Content 76
3.2.3.2 Volatile solids 76
3.2.3.3 Percent Carbon 77
3.2.3.4 Total Kjeldahl Nitrogen (TKN) 77
3.2.3.5 Particle Density and Porosity Determination 78
3.2.3.6 Oxygen Uptake Rates (OUR) 79
3.2.4 Laboratory Analyses - Water Extracts 80
3.2.4.1 Total Organic Carbon (TOC) Content 80
3.2.4.2 Organic and Ammonia Nitrogen 81
4.0 RESULTS AND ANALYSIS 82
4.1 Factorial Experiments 82
4.1.1 Trends in Operational Variables 82
4.1.1.1 C:N ratio 82
4.1.1.2 Moisture Content 88
4.1.1.3 Porosity Adjustment 95
4.1.2 Trends in Response Variables 101

4.1.2.1 Total Carbon 103
4.1.2.2 Total Organic Carbon (TOC) - Compost Water Extracts 110
4.1.2.3 C:Nw - Water Extract 116
4.1.2.4 Dry Bulk Density 121
4.1.3 Factorial Design Results 128
4.1.3.1 Factorial Experiment - Results 129
4.1.3.2 Factorial Results Discussion 132
4.1.3.3 Summary and Explanations 134
4.2 Decomposition 135
4.2.1 Decomposition Modelling 135
4.2.2 Comparison to Theoretical Model 141
4.2.3 Comparison of Individual Piles 145
4.2.4 Summary and Explanations 148
4.3 Temperature and % Oxygen Results 148
4.3.1 Trends in Pile Temperature and % Oxygen Readings 149
4.3.2 Arima Analyses - Results 150
5.0 SUMMARY AND CONCLUSIONS 153
6.0 REFERENCES 156
7.0 APPENDICES 166
Appendix A - Solid Sample Parameter Data 167
Appendix B - Density And Porosity Data 178
Appendix C - Water Extract Parameter Data 183
Appendix D - Temperature and Oxygen Data and Plots 188
D.1b Pile Temperature and Oxygen Plots 200
Appendix E - Factorial Results Summary 217
Appendix F - Decomposition Model Summary 226

LIST OF TABLES

Table		Page
2.1	Composition of Organic Wastes	7
2.2	Chemical Composition of Straw, Grass and Wood	9
2.3	C:N ratio of Various Wastes	17
2.4	Maximum Permissible Moisture Contents	19
2.5	Kinetic Constants of the Whang and Meenaghan Model	47
2.6	Compost Equilibrium Values for Different Mixtures	50
2.7	Decomposition Rate for Various Materials	52
3.1	Experimental Levels	61
3.2	Response Variables and Maturity Indicators	62
3.3	Factorial Design Matrix-1	63
3.4	Pile Descriptions	66
3.5	Windrows - Days Turned	67
3.6	Pile Sections - Watering Days	68
3.7	Pile Section - Sampling Days	74
4.1	Initial and Final Pile C:N Values	87
4.2	Weighted Average % Moisture Content of the Piles	93
4.3	Pile Porosity	99
4.4	Pile Response Variable Values- Full Period	101
4.5	Pile Response Variable Values- Active Period	102
4.6	% Carbon Values - Solid Samples	108
4.7	Pile TOC Values - Water Extracts	115
4.8	Pile Final C:N_w ratio	120
4.9	Pile Dry Bulk Density Values	127
4.10	Factorial Experiment - Significant Effects	129
4.11	Ranking of Effects - Full Period	130
4.12	Ranking of Effects - Active Period	131
4.13	Rate Constants for % Carbon - Solid samples	137
4.14	Rate Constants for TOC - Water extracts	139
4.15	Composting Model Conditions	144
4.16	Piles Significantly Different- % C data	146
4.17	Piles Significantly Different- TOC data	147
4.18	ARIMA Analyses - Results	152
A.1	Solid Sample Parameter Data	168

A.2 Multiple Sample % Volatile Solids Statistics 176
A.3 ANOVA - Mean % Volatile Solids Values 177
B.1 Compost Densities and Porosity Data 179
C.1 Water Extract Parameter Data 184
D.1 Pile Temperature and Oxygen Data 189
E.1 Factorial Results Summary 218
F.1 ANOVA Results Decomposition Models 227
F.2 Comparison of Pile Decomposition Rates - % C data 228
F.3 Comparison of Pile Decomposition Rates - TOC data 229

LIST OF FIGURES

Figure ..... Page

3.1 Compost Pile Sections Layout 65

3.2 Reconfigured Compost Pile Sections Layout 70

3.3 Windrow X - Section - Measurement Locations 72

4.1 C:N ratio vs Composting Days - Piles 2 and 6 83

4.2 C:N ratio vs Composting Days - Piles 4 and 8 83

4.3 C:N ratio vs Composting Days - Piles 1and 5 84

4.4 C:N ratio vs Composting Days - Piles 3 and 7 84

4.5 C:N ratio vs Composting Days - Piles L2 and L4 85

4.6 C:N ratio vs Composting Days - Piles L1and L3 85

4.7 C:N ratio vs Composting Days - Piles C1 and C2 86

4.8 C:N ratio vs Composting Days - Piles R1, R2 and 7 86

4.9 M.C. vs Composting Days - Piles 2 and 6 89

4.10 M.C. vs Composting Days - Piles 4 and 8 89

4.11 M.C. vs Composting Days - Piles 1 and 5 90

4.12 M.C. vs Composting Days - Piles 3 and 7 90

4.13 M.C. vs Composting Days - Piles L2 and L4 91

4.14 M.C. vs Composting Days - Piles L1 and L3 91

4.15 M.C. vs Composting Days - Piles C1 and C2 92

4.16 M.C. vs Composting Days - Piles R1, R2 and 7 92

4.17 Porosity. vs Composting Days - Piles 6 and 8 95

4.18 Porosity. vs Composting Days - Piles 5 and 7 96

4.19 Porosity. vs Composting Days - Piles L3 and L4 96

4.20 Porosity. vs Composting Days - Piles R1 , R2 and 7 97

4.21 Porosity. vs Composting Days - Pile1 98

4.22 % C. vs Composting Days - Piles 2 and 6 103
4.23 % C. vs Composting Days - Piles 4 and 8 104
4.24 % C. vs Composting Days - Piles 1 and 5 104
4.25 % C. vs Composting Days - Piles 3 and 7 105
4.26 % C. vs Composting Days - Piles L2 and L4 105
4.27 % C. vs Composting Days - Piles L1 and L3 106
4.28 % C. vs Composting Days - Piles C1 and C2 106
4.29 % C. vs Composting Days - Piles R1, R2 and 7 107
4.30 TOC. vs Composting Days - Piles 2 and 6 110
4.31 TOC. vs Composting Days - Piles 4 and 8 111
4.32 TOC. vs Composting Days - Piles 1 and 5 111
4.33 TOC. vs Composting Days - Piles 3 and 7 112
4.34 TOC. vs Composting Days - Piles L2 and L4 112
4.35 TOC. vs Composting Days - Piles L1 and L3 113
4.36 TOC. vs Composting Days - Piles R1, R2 and 7 113
4.37 C:N_W. vs Composting Days - Piles 2 and 6 116
4.38 C:N_W. vs Composting Days - Piles 4 and 8 117
4.39 C:N_W. vs Composting Days - Piles 1 and 5 117
4.40 C:N_W. vs Composting Days - Piles 3and 7 118
4.41 C:N_W. vs Composting Days - Piles L2 and L4 118
4.42 C:N_W. vs Composting Days - Piles L1 and L3 119
4.43 C:N_W. vs Composting Days - Piles R1, R2 and 7 119
4.44 DBD. vs Composting Days - Piles 2 and 6 122
4.45 DBD. vs Composting Days - Piles 4 and 8 123
4.46 DBD. vs Composting Days - Piles 1 and 5 123
4.47 DBD. vs Composting Days - Piles 3 and 7 124
4.48 DBD. vs Composting Days - Piles L2 and L4 124

4.49 DBD. vs Composting Days - Piles L1 and L3.....125
4.50 DBD. vs Composting Days - Piles C1 and C2.....125
4.51 DBD. vs Composting Days - Piles R1, R2 and 5.....126
D.1 Pile Temperature vs Composting Days - Pile 1.....201
D.2 Pile Temperature vs Composting Days - Pile 2.....201
D.3 Pile Temperature vs Composting Days - Piles 3 202
D.4 Pile Temperature vs Composting Days - Piles 4 202
D.5 Pile Temperature vs Composting Days - Piles 5.....203
D.6 Pile Temperature vs Composting Days - Piles 6.....203
D.7 Pile Temperature vs Composting Days - Piles 7 204
D.8 Pile Temperature vs Composting Days - Piles 8 204
D.9 Pile Temperature vs Composting Days - Piles R1 205
D.10 Pile Temperature vs Composting Days - Piles R2 205
D.11 Pile Temperature vs Composting Days - Piles L1 206
D.12 Pile Temperature vs Composting Days - Piles L2 206
D.13 Pile Temperature vs Composting Days - Piles L3 207
D.14 Pile Temperature vs Composting Days - Piles L4 207
D.15 Pile Temperature vs Composting Days - Piles C1 208
D.16 Pile Temperature vs Composting Days - Piles C2 208
D.17 Pile % Oxygen vs Composting Days - Piles 1 209
D.18 Pile % Oxygen vs Composting Days - Piles 2 209
D.19 Pile % Oxygen vs Composting Days - Piles 3 210
D.20 Pile % Oxygen vs Composting Days - Piles 4 210
D.21 Pile % Oxygen vs Composting Days - Piles 5 211
D.22 Pile % Oxygen vs Composting Days - Piles 6 211
D.23 Pile % Oxygen vs Composting Days - Piles 7 212
D.24 Pile % Oxygen vs Composting Days - Piles 8 212

D.25 Pile % Oxygen vs Composting Days - Piles R1 213
D.26 Pile % Oxygen vs Composting Days - Piles R2 213
D.27 Pile % Oxygen vs Composting Days - Piles L1 214
D.28 Pile % Oxygen vs Composting Days - Piles L2.....214
D.29 Pile % Oxygen vs Composting Days - Piles L3 215
D.30 Pile % Oxygen vs Composting Days - Piles L4 215
D.31 Pile % Oxygen vs Composting Days - Piles C1 216
D.32 Pile % Oxygen vs Composting Days - Piles C2.....216
E.1 Half Normal Plot- TOC - Full Period.....222
E.2 Half Normal Plot- DBD - Full Period.....223
E.3 Half Normal Plot- TOC - Active Period.....224
E.4 Half Normal Plot- DBD - Active Period.....225

Evaluation of Operational Parameters on Yard Waste Composting Performance

1.0 INTRODUCTION

1.1 Problem Statement

Urban centres in Canada develop a large amount of yard waste during the spring, summer and fall seasons. For example, an Ontario waste composition study indicated 10 to 15 percent of the waste stream by weight is organic yard waste (Obermeir and Riccius 1992). Most of the waste is sent to landfills for disposal but composting is now becoming a more favourable waste management option. Due to public awareness and concern, it is becoming more difficult to develop new landfills. Composting of yard waste increases the active life of the existing landfills and develops a useful product for horticultural and agricultural purposes.

In Canada, the period of active composting is limited by climatic conditions. Lower external temperatures in the winter and fall seasons affect biological activity. As temperature decreases towards 0^0C, metabolic functions of the microorganisms are suppressed and, hence, the rate of degradation of organic wastes is greatly reduced (Bellamy *et al.* 1992). The short period of active composting increases the composting time, the required land space and delays the possible sale and use of the compost.

1.2 Thesis Objectives

The goal of this research was to identify practical means to optimize the process of composting yard waste materials under local climatic and field conditions and hence reduce the time required to produce a mature and stable compost product. The specific objectives of the study were:

1. To systematically evaluate the influence of key operational parameters on the decomposition rate; and
2. To identify a practical indicator of compost stability and maturity.

1.3 Thesis Structure

This thesis is structured into five sequential chapters: the introduction, composting theory, experimental design, results and analysis and conclusions of the research. Chapter 1 has outlined the problem statement, the research objectives, the scope and limitations of the research.

Chapter 2 describes the theory of composting starting with a definition of composting, a brief summary of the types of composting systems, and a discussion of the composting process. In order to optimize the composting process, it is essential to have a knowledge of the chemical composition of organic materials, compost microbiology, and to understand the various biochemical stages of the process and key factors that influence the rate of decomposition.

Chapter 2 also discusses compost maturity, its importance as an indicator of composting performance and quality and reviews a number of parameters proposed in literature. Finally the theory development concludes with a review of various decomposition models. The purpose of modelling the decomposition of organic wastes is to evaluate the biological degradation of these materials over time and provide a tool for optimization of the process. The overall goal of chapter 2 is to assist in the the development of a set of hypotheses to be tested experimentally.

Chapter 3 describes the experimental approach including the factorial design, the key operational and response variables and outlines the operational activities, and methods and main materials used for this research.

Chapter 4 presents and explains the results of the experiment including the trends in operational and response variables, and the factorial experimental results. The chemical changes in the compost material for the various pile sections over the composting period are modelled and are compared. Finally, the effects on the average pile temperatures of operational activities such as watering, mixing, adding wood chips and rebuilding the pile sections are discussed.

Chapter 5 makes conclusions based upon the experimental results, and provides recommendations and suggestions regarding research enhancements and future opportunities.

1.4 Scope and Limitations

This study involved the optimization of yard waste composting under local climatic and field conditions using the Windrow method of composting as selected by the City of Edmonton for their 1992 Clear Bag composting program. The equipment and operational methods used were generally similar to those used in the Clear Bag program. Studying the composting process under field conditions presented some inherent limitations.

First, environmental factors such as precipitation, wind and ambient air temperatures may influence the composting process, especially the moisture content and compost pile temperatures. For example, precipitation may increase the moisture content of the compost material.

Second, the available equipment and operational methods effected the material composition of the various pile sections of the windrows. The windrows were constructed and the materials mixed with a front end loader. The amount of yard waste, straw and wood chips used for each windrow pile section was roughly determined by the number of full front end loader buckets, as there were no scale facilities on site. The amount of straw and grass added to each

specific pile section determined the initial C:N ratio levels. It was very difficult to adequately mix the compost materials with a front end loader especially the pile sections with straw and grass mixtures. The inadequate mixing effected the ability to obtain representative pile samples. It was also difficult to control the amount of water added to each pile section using a fire hose.

Finally, the large number of piles in the study and the available resources and equipment for sample analyses influenced the frequency and number of compost samples collected and therefore, placed limitations on the ability to monitor the compost process. The more frequently the samples are collected the more often the moisture content of the piles could be adjusted. Also more data points would be available to calculate the rate of decomposition for each pile section. In addition, the collection and analysis of multiple samples per pile for each sample date would provide statistical mean values and standard errors for the variables.

2.0 THEORY DEVELOPMENT

2.1 Introduction

The composting process is a complex interaction between organic waste, a mixed population of microorganisms, moisture and oxygen. Composting is defined as a biooxidative process that: 1) involves a heterogeneous organic substrate in the solid state; 2) evolves by passing through a thermophilic phase and a temporary release of phytotoxin; and 3) leads to production of carbon dioxide, water, minerals and stabilized organic matter (Zucconi and de Bertoldi 1987). The decomposition of organic materials can occur under aerobic as well as anaerobic conditions.

Aerobic composting is generally emphasized because decomposition of organic materials occurs more rapidly and produces less odours than anaerobic composting. The following sections outline the types of composting systems and review and explain the composting process in terms of its basic principles and rate limiting factors. In addition, maturity parameters are reviewed and decomposition models are presented and discussed.

2.2 Composting Systems

Composting systems are divided into reactor and non-reactor systems. Non-reactor composting systems include types such as passive composting, windrows, and aerated piles. Reactor systems vary from simple compost bins to vessel reactors with mechanical agitation and forced aeration. The following discussion deals with non-reactor composting system alternatives because the research objectives involved the optimization of the low technology windrow method of composting selected by the The City of Edmonton for their Clear Bag program.

The first method, passive composting, involves placing the organic material into large piles and allowing the material to degrade over time with little or no agitation and management. The aeration rate is low, resulting in a slow rate of decomposition and possible anaerobic conditions depending upon the type of organic material (Rynk 1992).

The second method, windrow composting, involves placing compostable materials into long piles or windrows approximately 1.83 m high and 3.1 to 6.1 m wide. These large size windrows tend to be self-insulating and retain enough heat to promote thermophilic activity (Biddlestone *et al.* 1987). The materials in the windrows are frequently turned or mixed with front end loaders or specially designed equipment and moisture is added if required. The windrows are turned to provide some aeration, and to homogenize and break down the materials into smaller particles, and to cool the compost piles if the temperature exceeds the optimum. The windrows are usually turned more frequently during the first few weeks of the process when the oxygen demand is high.

The final non-reactor method is the use of aerated static piles. The organic materials are piled into static windrows which have passive or forced aeration systems. A typical passive aeration system involves placing a series of perforated pipes approximately 30 to 45 cm apart, perpendicular to the longnitudinal axis of the windrow (Mathur 1992). The pipes are usually placed on a thin bed (15 cm) of rigid material such as straw or wood chips to allow for air movement. The compostable materials are placed on top of the pipes and are built into a windrow. The windrow is covered with mature compost or peat for insulation, odor and insect reduction.

A forced aeration static pile uses a blower to supply air or withdraw air from the windrow. Suction systems draw air into the pile from the outside environment, into the piping system and out an exit pipe end where the blower is located. Positive pressure systems blow outside air into and through the pile via the piping system. The piping for a forced aeration static pile typically consists of one or more longitudinal pipes with a central blower.either located at one end of the windrow or attached to a length of pipe connected perpendicular to the longitudinal pipe.

In summary, composting systems are divided into reactor and non reactor systems. Non reactor systems include passive composting, windrow composting and aerated static pile systems. The windrow composting method is more effective than passive

composting, but does not require the capital expenditures to install piping and blowers.

2.3 Chemical Composition of Organic Materials

Organic wastes amenable to composting include such materials as yard waste, sewage sludge, urban waste, crop residues, and animal manures. Waste materials whether industrial, urban or agricultural in origin are mixtures of sugars, hemicelluloses, celluloses, proteins, fats, lignins and minerals in a wide range of concentrations (Biddlestone *et al.*1987) Biddlestone *et al.*(1987) list typical ranges for the composition of organic wastes in Table 2.1.

Table 2.1 - Composition of Organic Wastes

Fraction	% Dry Weight
Hot/Cold water solubles (sugars, starches,amino acids,urea, ammonium salts)	2- 30%
Ether/alcohol solubles (fats,oils,waxes)	1-15%
Cellulose	15-60%
Hemicellulose	10-30%
Lignin	5-30%
Protein	4-40%
Ash	5-25%

The chemical components of compostable organic materials can be divided into three main fractions: carbohydrates, lignin, and nitrogen compounds. Carbohydrates, the primary fraction, include simple sugars, celluloses and hemicelluloses and are made up of carbon, hydrogen and oxygen atoms. Simple sugars, also called monosaccharides, contain three to six carbon atoms and are very water soluble. Glucose, with the structural formula $C_6H_{12}O_6$, is the main energy-supplying molecule of living cells (Tortora *et al* 1992).

Cellulose, the most abundant constituent of plant residues, often is associated with hemicellulose and lignin (Paul and Clark 1989). Cellulose is composed of monomeric glucose units joined together in a long, linear chain by ß-linkages at carbon atoms 1 and 4 of the sugar molecule (Alexander 1961). It occurs in a

semicrystalline state with a molecular weight of 10^6 and is insoluble in water (Paul and Clark 1989).

Hemicellulose, the second largest constituent of plants, is a polymeric material containing the hexoses; glucose, mannose, galactose and the pentoses xylode and aribinose (Lynch 1992). In the pure state, hemicelluloses are easily decomposed, but they are frequently complexed with other substances such as lignin that may make degradation more difficult (Paul and Clark 1989).

The second main fraction, lignin, is the third most abundant constituent of plant tissues and crop residues (Alexander 1961). The structure of lignin is based on the propanoid unit, which consists of an aromatic ring and a three-carbon chain (Paul and Clark 1989). Formed by polycondensation, lignin is not formed by a specific enzyme but in a chemical reaction involving phenols and free radicals (Paul and Clark 1989). During polymerization, secondary reactions lead to cross-linking between lignin and hemicelluloses making lignin particularly recalcitrant to microbial degradation (Lynch 1992). Table 2.2 summarizes typical values for the chemical composition of grass, straw and wood.

Table 2.2 - Chemical Composition of Straw, Grass and Wood

Organic Material	Chemical Constituent - % Dry Matter					
	Water Soluble	Cellulose	Hemicellulose	Lignin	Crude Protein	Ash
Barley Straw (a)	6	40	39	13	1	
Barley Straw (b)		37	44	11	4	7.1
Wheat Straw (a)	4	43	36	14	1	
Wheat Straw (b)		39		14	3.6	7.8
Couch Grass (a)	39	18	23	12	3	
Fresh Grass (b)*		20	17		14	8
Fresh Mature Grass (b) *		34	21	6	9.5	6.2
Pine wood (c)		44	26	27.8		
Birch Wood (c)		40	39	19.5		

* Kentucky Bluegrass

(a)- Lynch 1979
(b)- Subcommittee on Feed Composition,1982
(c) - Lynch 1987

Young succulent vegetation, including grasses and legumes contain higher relative proportions of water soluble organic matter and cellulose, while cellulose and lignin are major constituents in mature woody matter (Bellamy *et al.* 1992). As plants age, minerals tend to return to the soil and low molecular weight compounds are converted to higher molecular weight compounds especially in hemicellulose and lignin (Biddlestone *et al.* 1987). Grass contains a higher water soluble fraction compared to wheat and barley straws.

The last main fraction is organic and inorganic nitrogen including proteins, amino acids, urea, nitrate, nitrite and ammonium compounds. Proteins are organic molecules consisting of carbon, oxygen, hydrogen and nitrogen atoms. They are formed by the union

of alpha-amino acids which contain at least one carboxyl group and one amino group attached to the same carbon (Tortora *et al.* 1992). Nitrate, nitrite and ammonium compounds are inorganic forms of nitrogen.

In summary, the chemical components of compostable organic materials can be divided into three main fractions: carbohydrates, lignin, and nitrogen compounds. Carbohydrates, the primary fraction, include simple sugars, celluloses and hemicelluloses. Cellulose, is composed of monomeric glucose units joined together in a long, linear chain and are insoluble in water. Hemicellulose is a polymeric material containing hexoses and pentoses and is frequently complexed with other substances such as lignin. The second main fraction, lignin, is based on the propanoid unit, which consists of an aromatic ring and a three carbon chain. Cross-linking between lignin and hemicelluloses make lignin particularly recalcitrant to microbial degradation. The last main fraction is organic and inorganic nitrogen including proteins, amino acids, urea, nitrate, nitrite and ammonium compounds.

Grass contains a higher water soluble and lower cellulose, hemicellulose and lignin fractions compared to wheat and barley straws.

2.4 Microbiology and Process Principles

2.4.1 Microbiology

Composting is a dynamic microbial process brought about by the activities of various microbial groups capable of growing under varying environmental conditions in the compost pile (Biddlestone *et al.* 1987). No single species is able to break down and utilize all substrates to complete the decomposition process (Bellamy *et al.* 1992). The three major classifications of microorganisms participating in the composting process are: bacteria, fungi, and actinomycetes, although actinomycetes have been regarded as being higher forms of bacteria (Golueke 1977). Other organisms encountered in the composting process include microflora; algae and viruses, protozoa and small soil animals such as worms, ants and

mites. (Biddlestone *et al.* 1987). These macro-organisms play a role in mixing, breaking down and consuming compostable materials (Campbell 1990).

Bacteria, very small single - celled organisms, are the most numerous microorganisms in the compost pile and are responsible for the initial decomposition of the organic material (Golueke 1991).

Fungi which are larger than bacteria may be unicellular or multicellular and can be broadly divided into two groups, yeasts and molds (Haug 1993). Molds are aerobic and form long filaments that branch and intertwine (Tortora *et al.* 1992). Fungi, in addition to utilizing the same substrates as bacteria, are capable of decomposing cellulose and other decay-resistant substances and are quite prominent in the latter stages of composting (Rynk 1992). Fungi usually grow better in an acidic pH (5.0) (Tortora *et al.* 1992).

Actinomycetes form filaments like fungi and are small like bacteria, but have enough unique properties to be considered separate from bacteria and fungi (Golueke 1991). They are mostly aerobic and are more visible during the later stages of composting when the more resistant organic materials prevail. Actinomycetes can use a wide variety of compounds including organic acids, sugars, starches, hemicellulose, cellulose, proteins, polypeptides, amino acids and a large numbers of other organic compounds (Golueke 1991). They can grow in low moisture environments but have a low tolerance to acidic conditions (Rynk 1992).

Microorganisms can be classified according to the temperature range in which they best grow and reproduce. The three classifications are psychrophilic, mesophilic and thermophilic. The optimum temperature ranges as defined by Atlas and Bartha (1987) are listed below:

Classification	**Optimum temperature Range**
psychrophilic	5 - 15 ^{0}C
mesophilic	20 - 45 ^{0}C
thermophilic	40 - 60 ^{0}C

2.4.2 Composting Stages

Biddlestone *et al.* (1987) divided the composting process into four temperature-related stages: mesophilic, thermophilic, cooling down and maturation. Other authors divided the process into two stages; the active composting or bio-oxidative stage and the maturation or curing stage (Jimenez and Garcia 1992; Keener *et al.* 1992; Marugg *et al.* 1993). The following section first describes the various temperature related stages then discusses the characteristics of the two stage categorization.

Biddlestone *et al.* (1987) characterized the mesophilic stage, as a period of rapid microbial growth. The microorganisms, especially bacteria, consume the readily available organic substrates, such as sugars, and multiply, resulting in an increase in the compost pile temperature from ambient to about 40^{0}C within 1 to 2 days. As microbial activity increases, oxygen consumption increases. During this stage, organic acids are eventually formed resulting in a drop in pH to the acidic range. Fungi are able to grow and multiply in this acidic environment. As the temperature increases above 40^{0}C the mesophilic organisms die off and the thermophilic organisms flourish.

During the thermophilic stage, the more readily degradable substances such as simple sugars, starch, fat, proteins, are quickly consumed and the compost pile temperature continues to increase to above 60^{0}C (Biddlestone *et al.* 1987). With the higher temperatures, moisture losses occur due to evaporation and the pH of the compost material turns alkaline due to volatilzation of ammonia. Above 60^{0}C, microbial activity decreases significantly as the fungi are deactivated, and spore-forming bacteria and actinomycetes prevail (Golueke 1972). After the peak temperature period is reached, the compost mass enters a cooling stage marked by a decrease in compost pile temperature. Mesophillic microorganisms reinvade the compost pile. There may be several peak temperatures observed during the composting process depending upon the type of operation (Rynk 1992). For example, if the oxygen availability decreases, microbial activity decreases resulting in a drop of compost mass

temperature. Aerating the pile results in an increase in microbial activity and the return to higher temperatures.

During the cooling stage, thermophilic fungi and actinomycetes attack the more resistant hemicellulose and cellulose fractions breaking them down to simple sugars which may be used by variety of microorganisms (Biddlestone *et al.* 1987). The compost pile temperature continues to drop to ambient conditions due to lower microbial activity and decomposition rate.

The final stage, maturation, is marked by small losses in mass and moisture, low oxygen consumption, heat generation and compost temperatures (Rynk 1992). The decomposition of the more resistant materials continues at a very low rate and humic compounds are formed. The maturation stage helps to ensure the compost has matured so it has no adverse effects on growth of plants.

Marugg *et al.* (1993) divided the composting process into an active phase and the maturation or curing phase. They subdivided the active phase into an initial period and a principle phase. The initial active phase was described as a period of exponential microbial growth at the start of the process, when some of the more readily available organic substrates are consumed. The principle active phase involves the decomposition of the available substrates by microorganisms over a longer period of time. The final stage, the curing stage is marked by a lower decomposition rate.

2.4.3 Process Steps

As previously mentioned, composting can be carried out under aerobic or anaerobic conditions. Aerobic composting is generally emphasized because decomposition of organic materials occurs more rapidly and produces less odours. The following paragraphs discuss the main steps of the aerobic composting process.

Aerobic composting is a dynamic process involving a number of complex steps leading to the oxidation of organic compounds, growth of microbial biomass and the formation of humic materials. The overall process can be represented in simplified terms by the following equation (City of Edmonton 1991):

Organic Materials + O_2 —*microbial metabolism*→ **stabilized organic residue** + CO_2 + H_2O + heat + biomass (1)

After the initial oxidation of readily-available, water-soluble compounds in the compost mass, the first main step in the composting process involves hydrolysis of polymeric material. Heterotrophic bacterial cells and fungi excrete extracelluar enzymes that catalyze hydrolytic reactions producing lower molecular weight water soluble organic compounds. For example, cellulase enzymes catalyze the degradation of cellulose. C_1 enzymes act on native cellulose and C_x enzymes break up partially degraded polymers resulting in the disaccharide cellobiose (Atlas and Bartha 1987). Cellobiose is hydrolyzed to glucose by the enzyme cellobiase (Paul and Clark 1989). Complex carbohydrates must be broken down to at least disaccharides and proteins to alpha-amino acids before the organic compounds are small enough to diffuse through the cell wall of bacteria where they are used for energy, synthesis of cell material and other organic compounds (Sawyer and McCarty 1978).

The second major step in the aerobic decomposition of organic compounds involves respiration, the oxidation of the substrate within the organism. Intracellular enzymes known as desmolases act as catalysts for oxidation-reduction reactions (Sawyer and McCarty 1978). Respiration involves a series of oxidation-reduction reactions resulting in the production of CO_2 and H_2O and heat.

The final product of the decomposition process is called compost which contains stabilized organic residue, biomass. It is often referred to as humus, because it consists of humic material. Humic material is formed by the polymerization of monomeric constituents such as phenols, quinones, amino acids and sugars by spontaneous chemical rections catalyzed by microbial enzymes (Atlas and Bartha 1987).

2.4.4 Section Review

Composting is a dynamic process brought about by the activities of various microbial groups including bacteria, fungi, and actinomycetes. Bacteria are responsible for the initial decomposition of the organic material. Fungi utilize the same

substrates as bacteria, but are capable of decomposing cellulose and other decay resistant substances and are quite prominent in the latter stages of composting. Actinomycetes can use a wide variety of compounds including organic acids, sugars, starches, hemicellulose, cellulose, proteins, polypeptides, amino acids and a large numbers of other organic compounds. They are more visible during the later stages of composting.

The composting process can been divided into four temperature-related stages: mesophilic, thermophilc, cooling down and maturation or into two stages; the active composting or bio-oxidative stage and the maturation or curing stage.

Aerobic composting is a dynamic process involving a number of main complex steps including the hydrolysis of polymeric material and the oxidation of the substrate within organisms resulting in the production of CO_2 and H_2O and heat, microbial biomass and the formation of humic materials.

2.5 Rate Limiting Factors

There are a number of factors which influence the composting process, mainly by affecting the rate of growth and degree of microbial activity. The principal environmental factors in composting are nutrient concentration and availability, moisture, oxygen concentration, temperature, and pH level (Golueke 1977; Finstein and Miller 1984; de Bertoldi *et al.* 1983; Mathur 1991; Bellamy *et al.* 1992).

2.5.1 Nutrient Concentration and Availability

The decomposition of organic matter provides microorganisms energy for growth and supplies carbon and other nutrients for the formation of new cell material (Alexander 1961). In addition to carbon, microorganisms require macronutrients nitrogen, phosphorus, sulphur, potassium, calcium, magnesium, iron and various trace metals such as cobalt and zinc (Bellamy *et al.* 1992; Biddlestone *et al.* 1987; Golueke and Diaz 1990).

Nitrogen is a critical nutrient for microbial growth and it is a major constituent of protoplasm (Golueke and Diaz 1990). On average, microorganisms contain 50% carbon, 5% nitrogen and 0.25-1.0% phosphorus on a dry basis (Biddlestone *et al.* 1987). Paul and Clark (1989) indicated soil organisms generally have been shown to have a C:N ratio of 5:1 to 8:1 and most microbial cells contain approximately 45% carbon and a 6 to 9% nitrogen. The values for % carbon and nitrogen differ in the sources quoted above, but the percentage values clearly indicate the importance of both elements. Nitrogen is the most significant limiting nutrient in soil and composting matter (Bellamy *et al.* 1992).

In terms of nutrient balance, the carbon to nitrogen (C:N) ratio is considered an important parameter in the composting process. Several authors discussed optimum C:N values of waste materials for composting. Biddlestone *et al.* (1987) and de Bertoldi *et al.* (1983) suggested an initial C:N ratio of about 25:1 should be optimum if no nitrogen is lost. Goleuke and Diaz (1990) stated generally the optimum C:N ratio is between 19 to 30 parts available carbon to 1 part available nitrogen. Above a C:N ratio of 30:1 the use of the available nitrogen to meet the metabolic needs of the microorganisms will predominate over organic matter decomposition and organic N mineralization to ammonium (NH_4^+) and nitrate (NO_3^-) (Bellamy *et al.* 1992). At C:N ratios lower than 18 or 19:1 there is an excess of nitrogen and ammonia volatilizes to the atmosphere and the pH level may rise to inhibitory levels (Golueke and Diaz 1990). Golueke and Diaz (1990) also suggested an excess of ammonia may be toxic to some microbes. The activity of nitrogen-fixing bacteria during the latter mesophilic temperature stage help offset the the loss of nitrogen by volatilization (Biddlestone *et al.* 1987).

The optimum C:N ratio is a function of the compositional nature of the organic wastes, especially the carbon content (Golueke 1977). Golueke (1977) explained if the carbon is bound in compounds more resistant to microbial attack, then the carbon would become only slowly available to the microbes and the permissible C:N ratio could be higher. Most of the nitrogen in wastes is readily available

except for small amounts of nitrogen resistant nitrogen compounds such as keratin (Golueke 1977). Representative values for the total C:N ratio for various organic materials is shown in Table 2.3.

Table - 2.3 C:N Ratio of Various Wastes
from Golueke,1977

Material	Nitrogen % of Dry Weight	C:N Ratio
Night Soil	5.5-6.5	6-10
Urine	15-18	0.8
Blood	10-14	3
Animal Tankage		4.1
Cow Manure	1.7	1.8
Poultry Manure	6.3	15
Sheep Manure	3.8	
Pig Manure	3.8	
Horse Manure	2.3	25
Raw sewage sludge	4-7	11
Digested sewage sludge	2-4	
Activated sludge	5	6
Grass clippings	3-6	12-15
Non legume vegetable wastes	2.5-4	11-12
Mixed grasses	214	19
Potato tops	1.5	25
Straw,wheat	0.3-.05	128-150
Straw, oats	1.1	48
Sawdust	0.1	200-500

The total C:N ratios of sawdust and wheat straw are relatively high compared to the other materials. As previously discussed, wood and straw have significant lignin content. The degree of lignin binding to other constituents of lignocellulose (cellulose and hemicellulose) is one of the major factors affecting the ability of micro-organisms to biodegrade straw and other plant materials (Lynch 1992). For practical purposes, the carbon content in wood chips and sawdust is not readily available: therefore, they should be basically considered as bulking and moisture absorption agents (Golueke and Diaz 1987).

The lowering of the C:N ratio by increasing the nitrogen content of the waste does improve the decomposition of cellulose and lignin (Bellamy *et al.* 1992). High C:N ratio materials may be effectively lowered by adding high nitrogen content materials such as grass clippings (Golueke and Diaz 1990). Alexander (1961) indicated the addition of inorganic nitrogen enhanced the decomposition of cellulose up to a C:N ratio of 35:1. Bellamy *et al.* (1992) suggested that, above this ratio, the additional nitrogen would probably be converted to ammonia gas or nitrogen. Hankin *et al.* (1976) added granular urea, a readily available source of nitrogen, to layers of leaves to reduce the C:N ratio. They found the urea is utilized within the first 4 days and that a long-term slow release form of nitrogen is needed. Golueke (1977) indicated the permissible C:N ratio for wastes containing a large amount cellulose, hemicellulose and lignin can be as high as 35:1 and perhaps 40:1.

If the C:N ratio of organic materials is below the optimum, easily degradable carbon materials can be added to increase the C:N ratio. Witter and Lopez-Real (1988) noted researchers found the addition of carbonaceous material was shown to be an effective solution to reducing these nitrogen losses, as the ammonia formed becomes rapidly immobilized into new microbial biomass.

The C:N ratio of the composting mass decreases throughout the process. The C:N ratio decreases because about two thirds of the carbon consumed by the microorganisms is given off as CO_2, while the other third is combined with nitrogen in the living cell (Golueke 1977). Based on an average composition of 50 % carbon and 5 % nitrogen for microorganisms, for every unit of nitrogen 10 units of carbon are assimilated and 20 units are given off as CO_2 (Alexander 1961). Upon the death of microbes, the carbon and nitrogen is again made available to the active microbes for decomposition. Alexander (1961) indicated the process is repeated until the equilibrium C:N ratio is reached and the organic nitrogen mineralized is no longer needed for microbial growth but stays in the mineral form. He suggested an equilibrium C:N ratio of about 10:1 based on the average composition of microorganisms.

2.5.2 Moisture Content

Moisture content is a critical rate-limiting factor for microbial life and the decomposition of organic matter (Bellamy *et al.* 1992). Biological activity takes place in the aqueous phase or at the interface of the water, solid compost and gas phases (Hamelers 1992). Microbial cells consist of 70-90% water by weight and all chemical reactions which occur in the cytoplasm of a cell take place in an aqueous environment (Brock and Madigan 1991). Water serves as both a solvent and a medium for mass transfer of enzymes, nutrients, gases, and waste products within and outside the cell. For example, the hydrolysis of complex carbohydrates is required before the cell can absorb the dissolved nutrients through its cellular membrane. Under low moisture conditions, the mass transport of soluble components are hindered (Haug 1980).

Haug (1980) indicated the optimum moisture level is between 50 and 65%. Below 50% moisture content, microbial activity is limited and all biological activity ceases at a moisture content of 12% (Golueke 1977). Golueke (1977) emphasized the maximum permissible percent moisture is a function of the physical nature of the material to be composted. For example, fibrous or bulky materials such as straw and wood chips can absorb relatively large amounts of water and still maintain adequate porosity (Haug 1980). Table 2.4 lists maximum permissible moisture contents for different types of wastes.

Table 2.4 - Maximum Permissible Moisture Contents
from Golueke, 1977

Type of Waste	Moisture Content % of Total Weight
Straw	75-85
Wood (sawdust, wood chips)	75-90
Rice hulls	75-85
Wet wastes (vegetable trimmings, lawn clippings, garbage ,etc.	50-55
Municipal refuse	55-65
Manures (without bedding)	55-65

Haug (1980) qualified the moisture requirements by stating "moisture levels must be high enough to assure adequate rates of biological stabilization, yet not so high that void spaces are eliminated, thus reducing the rate of oxygen transfer and in turn, the rate of biological activity ".

Moisture requirements vary with changing composition of the microbial population. A high moisture level is required during the initial decomposition stage in which bacteria prevail (Zucconi and de Bertoldi 1987). In the initial stage, the more easily decomposed substrates are utilized resulting in rapid growth of the bacterial population and an increase in temperature of the compost mass. The increase temperature of the compost pile will result in moisture losses due to evaporation. Moisture content requirement is lower during the stabilization stage when the fungi and actinomycetes prevail (Zucconi and de Bertoldi 1987). Haug (1980) noted fungi are less affected by low moisture conditions. He did not specify a specific moisture percent. Haug indicated fungi can grow on dry substrates with moisture obtained from surrounding air.

2.5.3 Aeration - Oxygen Concentration

The availability of oxygen during the composting process is very important. Oxygen is used by microorganisms as a terminal electron acceptor for aerobic respiration and also in the oxidation of several sorts of organic substances in the mass (Zucconi and de Bertoldi 1987). The stoichiometric oxygen required for oxidization can be calculated from the chemical composition of the organic materials. The compost pile will usually contain a mixture of materials with different theoretical oxygen demands and varying degrees of degradability.

Oxygen requirements vary throughout the process. Oxygen demand is very high during the initial decomposition stage when the readily available organic compounds are being degraded and the microbial population is increasing rapidly (Zucconi and de Bertoldi 1987). The need for oxygen decreases during the cooling and maturation stages but a minimum concentration of 5% oxygenin the gas phase has been suggested for the thermophilic stage

(Biddlestone *et al.* 1987). Haug (1980) indicated various studies show an increase in the rate of oxygen uptake with increasing temperature with maximum rates at temperatures between 45^{0}C to 60^{0}C and decreasing rates at higher temperatures.

Haug (1980) indicated oxygen must be provided to any composting material in order to meet the demands imposed by organic decomposition. The methods used to aerate the compost mass include passive aeration, mechanical turning and mixing and forced aeration or a combination of these methods. The first method, passive aeration, involves the mass movement of air from the windrow exterior, through the pore spaces to the interior of the windrow. The two mechanisms of passive aeration discussed by Haug (1980) are by molecular diffusion and by the mass movement of air through the pores in response to a temperature gradient. Molecular diffusion is the movement of air from the zone of high oxygen concentration to zone of low concentration. Haug (1980) cited previous studies by Shell and Snell that indicated the molecular diffusion process is extremely slow and contributes only a small percentage to the total oxygen demand required during composting (Haug 1980).

Haug (1980) suggested the primary means of passive aeration is by convection caused by the density difference between the warm moist air within the interior of the compost pile and the colder less moist ambient air. He said the hot air within the interior of the windrow will flow upward resulting in outside air being drawn into the pile. Bellamy *et al.* (1992), believed that pile settlement and high moisture levels will limit pore volumes and air movement. They explained respiring, microbial populations will rapidly deplete the available oxygen, and that passive aeration does not meet the necessary oxygen requirements, resulting in anaerobic conditions. The addition of bulking agents such as wood chips to the compost mass increases the porosity which promotes natural ventilation (Haug 1980). Schultze (1962) stated a 30% minimum free air space (FAS) should be maintained in the compost material. The free air space is defined as the volume of gas to total volume of the compost mass.

Mathur (1992) successfully utilized a passive aeration system with numerous plastic pipes placed across the width of the windrow to compost seafood wastes. The heat generated by decomposition draws air through the intake pipes and into the compost mass. Mathur (1992) indicates the active composting stage was completed in 6 to 12 weeks when the interior core of the compost pile and the peat envelope reached similar temperatures.

The second aeration method involves turning and mixing the compost windrows with mechanical equipment such as front end loaders, tractors or more specifically designed equipment. Mechanical mixing helps homogenize the compost material in terms of composition, moisture content, aeration and reduces particle size. The effectiveness of mechanical aeration is dependent on the frequency of mixing, the amount of exposure and homogenization achieved during the process (Bellamy *et al.* 1992). Reinhart *et al.* (1991) found that windrow turning provides only a limited amount of aeration and oxygen levels rapidly return to their previous levels.

The third approach, forced aeration, uses a system of piping and fans to pump air through the pores of the the compost windrow. Many studies have been carried out on forced aeration of sewage sludge solids (Haug 1986; Finstein *et al.* 1986). The aeration rate of the windrow is controlled by a number of methods including manual intervention, timers, and feedback controls based on temperature, O_2, or CO_2.

Aeration also provides for the removal of CO_2, excess heat and moisture produced in the microbial reaction (Biddlestone *et al.* 1987).

2.5.4 Temperature

Temperature is a key factor affecting biological activity. All organisms live and function within a particular temperature range (Haug 1980). Generally, each group of organisms has an optimum temperature and any deviation from the optimum results in a decline in growth and activity of the organism (Golueke 1972). Within certain temperature ranges, the rates of biochemical reactions double for a 10^0C increase in temperature (Sawyer and McCarty 1978). There is a limit to the exponential increase because at high temperatures thermophilic microbes cannot overcome the effects of thermal denaturation (Haug 1980). Tortora *et al.* (1992) described denaturation of an enzyme as the loss of its characteristic three-dimensional structure due to the breakage of hydrogen and other noncovalent bonds. Denaturation changes the arrangement of the amino acids in the active site, and causes the enzyme to lose its catalytic ability (Tortora *et al.* 1992). The temperature required for efficient composting must be high enough to increase the rate of biochemical reactions, yet not too high to inhibit biological activity.

Various authors suggested different optimum temperature ranges for the composting process. Golueke (1972) said the range of optimum temperature for the composting process varies from about 35^0C to 55^0C because of the many groups of organisms taking part in the process. deBertoldi *et al.* (1983) suggested optimal temperatures vary from 45^0C to 55^0C, while Haug (1980) stated different investigators have found optimum values ranging from as low as 45^0C to above 70 ^{0}C

Despite the differences in optimum values, these authors agreed the composting process becomes less efficient at high temperatures. When the temperature of the compost pile exceeded 60^0C spore-forming organisms enter the spore resistant stage, and microbial activity is reduced to practically zero (Golueke 1972). deBertoldi *et al.* (1983) stated only a few thermophilc sporigenous show metabolic activity above 70^0C. A period of high temperatures is useful for killing some pathogens in the composting wastes (Thambirajah 1991).

High composting temperatures are the consequences of the biological activity and the heat given off in the decomposition of organic wastes. Depending upon the system of composting used, various operational activities including increasing aeration and watering are used to lower the temperature to within a more optimum range.

2.5.5 pH

The final environmental factor affecting composting is pH. The optimum pH range for most bacteria is between 6 and 7.5 and from 5.5 to 8.0 for fungi (Golueke 1972). Bacteria prefer a nearly neutral pH, whereas fungi grow better in an acidic environment (de Bertoldi *et al.* 1983; Tortora *et al.* 1992).

The pH of the compost substrate affects enzymatic activity of the microorganisms. Most enzymes have an optimum pH level at which their activity is a maximum (Tortora *et al.* 1992). Tortora *et al.* (1992) noted that when the pH deviates from the medium range the three dimensional structure of many of the enzyme's amino acids are altered resulting in the reduction of enzymatic activity.

Goleuke (1991) indicated the pH in a compost pile varies throughout the process. During the early mesophilic stage, the pH decreases as acid-forming bacteria break down complex material to organic intermediates (de Bertoldi *et al.* 1983). The pH increased to alkaline levels (>8) during the thermophilic phase due to the production of ammonia (Bellamy *et al.* 1992). Bellamy *et al.* (1992) noted the pH is neutral to slightly alkaline during the cooling and maturation stages.

Golueke (1972) stated that in a practical operation, little should be done to alter the pH of the compost pile due to the costs involved and the potential loss in nitrogen due to the volatilzation of ammonia. Bellamy *et al.* (1992) explained that the addition of lime may be necessary to adjust the pH for extreme acidic conditions in the compost pile, but generally do not think pH adjustment is required.

2.5.6 Section Summary

The principal rate limiting factors that influence the composting process are; C:N ratio, moisture, oxygen concentration, temperature, and pH level. The suggested optimum C:N ratio is between 19 to 30 parts available carbon to 1 part available nitrogen. A moisture level between 50 and 65% is considered optimal and that below 50% moisture content microbial activity is limited. All biological activity ceases at a moisture content of 12%. Oxygen is used by microorganisms as a terminal electron acceptor for aerobic respiration and a minimum concentration of 5% has been suggested for the thermophilic stage of the composting process. The optimum temperature range for the composting process is approximately between 45^0C to 55^0C, although investigators have suggested slightly different values. The optimum pH range for most bacteria is between 6 and 7.5 and from 5.5 to 8.0 for fungi (Golueke 1972). The composting of organic materials can be optimized by controlling the above mentioned rate-limiting factors. The operational variables C:N ratio, moisture content, and aeration are the most practical variables to control in a windrow composting experiment. Golueke (1972) stated that in a practical operation, little should be done to alter the pH of the compost pile due to the costs.

2.6 Compost Maturity Parameters

This section of the report defines compost maturity, explains why it is important, reviews most of the major parameters proposed in numerous studies and discusses some considerations for parameter selection. The terms maturity and stability are often used to characterize the condition or state of the compost product. Stability refers to the level of microbial activity of the compost and usually depends on some measurement of respiration rate (Frost *et al.* 1992). "Maturity is defined as the degree of decomposition of organic matter during composting." (Chen and Inbar 1992) Chen and Inbar (1992) proposed definitions for mature composts for agricultural and greenhouse uses. For greenhouse use, compost maturity is defined as organic matter composted to a degree that has no adverse effects on plants. The definition is basically the

same for agricultural uses except for the words "has no adverse effects on growth of various crops when applied at annual rates up to 50 tons/ha at least six weeks before planting or sowing." It appears that some authors use the words maturity and stability interchangeably.

Determining the maturity and or stability of a compost is essential for composting operations. Compost maturity serves as an indicator of process performance and product quality. Immature compost applied to a soil or used in potting mixes is phytotoxic to plants, reduces the nitrogen available for plant growth and creates unwanted odours (Mathur *et al.* 1992).

The organic intermediate products of the decomposition process such as low fatty acids and phenols retard seed germination and plant growth and excess ammonia can injure plant roots (Mathur *et al.* 1992). When immature compost with a high C:N ratio is added to soils, the microorganisms immobilize soil nitrogen to decompose the organic compounds resulting in less nitrogen available for the plants (Mathur *et al.* 1992). In addition, the continued decomposition of the organic compounds in immature compost depletes the oxygen concentration of the soil affecting root respiration and producing toxic anaerobic products H_2S and NO_2^- (Katayama *et al.* 1987).

The determination of compost maturity is very difficult due to the complexity of the process, and the different compositions of the various organic wastes. No single test has been found to indicate maturity for all composts: therefore, a series of parameters are usually measured (Inbar *et al.* 1990). There were many methods proposed in the literature to indicate compost maturity and the tests may be grouped into five categories: plant bioassays, microbial bioassays, chemical analyses, physical tests and spectroscopy (Inbar *et al.* 1990; Jimenez and Garcia 1989). Many of the tests required monitoring changes in properties of the compost from the beginning of the process to the point of stabilization. Some of the more frequently utilized maturity tests are seed germination or plant growth tests, change in organic carbon/organic nitrogen ratio of water extracts (C/N_W), cation exchange capacity (CEC), respiration rate of the compost, humification ratios, temperature and changes in

organic matter. The following sections review the major maturity test methods in each category.

2.6.1 Plant Bioassays

Plant bioassays are perhaps the most reliable and the ultimate test to indicate compost maturity, because any adverse effects on plant growth or seed germination are clearly indicated. (Chen and Inbar 1992) There are two general types of plant bioassays; plant growth tests and seed germination tests. Plant growth tests involve evaluating the growth of plants typically over a 2 to 3 week period; growing in compost potting mixtures or compost water extracts. In seed germination tests, seeds are placed on filter paper impregnated with compost extract in petri dishes and are incubated in the dark for about 24 hours. (Jimenez and Garcia 1989) The toxicity of the compost is based on the percentage of seeds that germinate.

Zucconni *et al.* (1981) planted a wide variety of plants in fresh, immature and mature high C/N composts to assess the effects on plant growth. Generally, they found all plants are inhibited by the immature compost. Inbar *et al.* (1990) used rye grass to assess the impact of cow manure compost on plant growth. The growth of rye grass is inhibited in both compost amended soils and compost water extracts during the early stages of the composting process. They note the inhibition of growth is related to water soluble phytotoxic substances in the immature compost. Although plant growth tests are very reliable, it takes at least 2 to 3 weeks before results are obtained.

Seed germination tests are easier than plant growth tests and provide results in a more timely manner. A common germination test evaluates the phytotoxicity of compost water extracts using Lepidium sativum L seeds, also known as watercress seeds Zucconi *et al.* (1981). From the germination results two parameters, % germination and a germination index were calculated. Zucconi *et al.* (1981) indicated a compost is not phytotoxic when the value of the germination index is over 80 to 85%. In contrast, Jimenez *et al.* (1989) stated a germination index above 50% for city refuse compost indicates an acceptable level of compost maturity. Riffaldi

et al. (1988) tested water extracts of fresh and three-month stabilized farm yard manure. The mean value of the germination index for the fresh manure was 35% compared to 60% for the stabilized manure. Based on these results, Riffaldi *et al.* (1988) indicated a 3 month stabilization period is not sufficient to reduce the phytotoxicity of the manure. Saviozzi *et al.* (1987) tested a wastewater sludge/chopped straw compost using the Lepium sativum L. seeds and observed no phytotoxic effects after 30 days.

2.6.2 Microbial Bioassays

Microbial bioassays evaluate the maturity of a compost based on the level of microbial activity. Methods include measuring microbial respiration rate, adenosine triphosphate (ATP) content of the compost, total microorganism count and identifying indicator microorganisms. During the early stages of the composting process, the microbial population is rapidly increasing, the ATP content increases and the oxygen consumption is very high. As the readily available organic compounds are consumed leaving the more resistant organic materials, the oxygen utilization rate (OUR) and ATP content of the compost decrease.

Firstly, respiration techniques such as biological oxygen demand (BOD) are used to characterize wastewater and soil scientists evaluate the decomposition of organic matter in soils by measuring CO_2 evolution rate. Respiration methods are also used to study the rate of decomposition of organic materials in composting operations. The methods used vary from monitoring the O_2 and CO_2 concentration in the input and output gases of pilot composting vessels using gas detection meters to measuring O_2 consumption or uptake rate (OUR) in reaction flasks (Schulze 1962; Kubota and Nakasaki 1991; Nakasaki *et al.* 1987; Zimmerman and Richard 1991; Willson and Dalmat 1986; Haug and Ellsworth 1991; Frost *et al.* 1992). The following sections review the microbial respiration rates measured in reaction flasks. Presently, there is no standard method or apparatus for measuring microbial respiration in reaction flasks. The standard BOD and chemical oxygen demand (COD) procedures are designed primarily for liquid waste samples (Haug

and Ellsworth 1991). Willson and Dalmat (1986) noted the established Warburg respirometer was not designed to handle large enough compost samples necessary to be representative of the hetergenous materials. Researchers have developed their own respirometers using standard laboratory equipment such as Erlenmeyer flasks and other basic equipment. Willson and Dalmat (1986) used a pressure gauge to monitor the change in vacuum of a second flask connected to the reaction flask. Haug and Ellsworth (1991) developed a simple constant pressure respirometer and Frost *et al.* (1992) used a dissolved oxygen probe to measure O_2 consumption in reaction flasks.

Willson and Dalmat (1986) observed the oxygen consumption rate of sewage sludge compost decreased over time and that 30 days of aerobic curing reduced the respiration rate by 75%. They also indicated there were possible errors in readings due to gas leaks in the tubing connections. Gas leaks represent a major concern for the effectiveness of repirometric techniques.

Haug and Ellsworth (1991) measured the oxygen uptake rate for sewage sludge. They found the OUR was high during the first 15 days of the test and then decreased gradually with no change between days 50 to 60. The substrate degradability was estimated to be 46% of the volatile solids by dividing the projected ultimate oxygen demand (cumulative) by the total oxygen demand in a chemical oxygen demand (COD) test.

Frost *et al.* (1992) measured the respiration rate of various municipal solid waste (MSW) compost samples over the composting period using a dissolved oxygen probe. Compost samples (60 g) were placed on nylon mesh platforms in 500 ml Erlenmeyer flasks. Water was added to the samples to bring the moisture content up to a minimum of 50 % (w/w). Humidified air was supplied to the compost reaction flasks at a rate of 2.5 L/min except when respiration measurements were made. The D.O. meter probes were inserted into rubber stoppers which were placed into the neck of the reaction flasks. Readings were taken every 10 minutes for 1 hour. By plotting the average % saturation values versus testing time, the slopes of lines for the different ages of compost samples are

compared. The steep slopes observed for the day 3 and 6 samples indicated a high oxygen demand by the microorganisms. The slopes of the lines flattened as the age of the compost sample increases and the oxygen demand decreases.

Zimmerman and Richard (1991) found that oxygen utilization rate is an excellent indicator of MSW stability. They measured OUR over a 10-day period for each sample and observed the OUR rate decreased as the age and stability of the compost increased. Respiration methods are a good test of compost stability, but no standard method has been adopted and the oxygen uptake or CO_2 evolution rate must be determined throughout the composting process.

Secondly, the measurement of ATP content or enzyme concentrations of a compost measures the quantity and level of microbial activity (Penninck and Verdonck 1987). The ATP content is high during the early stages of the composting process and decreases greatly during the thermophilic stage when microbial activity is generally inhibited (Jimenez and Garcia 1989). The ATP concentration is low in the latter stages of the composting process reflecting a reduced level of microbial activity. Penninck and Verdonck (1987) observed the mean ATP value of pine bark was 19283.52 µg ATP/kg of compost compared to 5928.86 µg ATP/kg of compost after composting. Jimenez *et al.* (1989) briefly reviewed the findings of Colin (1977). They found that the hydrolytic enzyme activity increased gradually during the maturation phase of refuse composting and decreased slightly after stabilization was observed at 140 days.

Finally, the total count and concentration of the various microbial species provides an indication of the stage of the composting process. Riffaldi *et al.* (1986) observed a rapid increase in proteolytic and ammonia-producing bacteria during the early stages of composting. They each reach a maximum count of approximately 10^6 to 10^7 per gram dry weight within 15 days and then their numbers decreased and were not detectable on the 60th day of composting (paper processing wastewater sludge amended with straw). Autotrophic nitrifying bacteria are inhibited during the

early stages when high temperatures and elevated ammonia concentrations prevailed (Riffaldi *et al.* 1986). The nitrifying bacteria are at a maximum count of about 10^6 per gram dry weight on the 80th day and are still present after 140 days of composting. Riffaldi *et al.* (1986) found celluloytic microorganisms, bacteria and fungi constantly increased up to the 60th day (10^6 per gram dry weight) and then, maintained the level throughout the composting process. Although these are not absolute indicators of maturity, they can be used to identify when the composting process enters the stabilization stage.

2.6.3 Chemical Analyses

Many chemical analyses that monitor the change in organic matter and its constituents throughout the composting process have been proposed as indicators of compost maturity. The chemical analyses of the solid phase include; C:N ratio, total organic matter, volatile solids, total carbon, oxidizable carbon, alkaline-extractable carbon, humic and fulvic-like carbon, total nitrogen and cation exchange capacity (CEC). From these chemical analyses, additional parameters such as humification ratio, humification index, percent humic acid and the ratio of humic acid to fulvic acid have been evaluated as potential maturity indexes. Since microbial metabolism is primarily in the water phase, chemical analyses of compost water extracts are also used (Saviozzi *et al.* 1987). Water soluble organic matter, TOC, organic carbon/organic nitrogen ratio, and pH are identified as indicators of compost maturity. The compost maturity indicators of the solid phase listed above are reviewed first, followed by the water extract parameters.

2.6.3.1 Solid Phase

The C:N ratio of the solid phase is traditionally used as a maturity parameter; however, various researchers indicated it cannot be considered as an absolute indicator of compost maturity (Hirai *et al.* 1983; Jimenez and Garcia 1991). Hirai *et al.* (1983) noted the C:N ratio of mature compostable materials varies from 5 to 20, depending upon the starting organic materials. Organic materials consist of varying amounts of chemical constituents.

These include cellulose and lignin with varying degrees of biodegradability. Based on the differences in chemicals constituents of the various organic materials, the final C:N ratio of the composts vary.

Changes of organic matter, volatiles and total carbon and oxidizable carbon, and organic components such as cellulose, hemicellulose and lignin as well as nitrogen content are also used to evaluate the stability of compost (Riffaldi *et al.* 1986; Hammouda and Adams 1987; More and Sana 1987; Jimenez and Garcia 1991; Jimenez and Garcia 1992a; Jimenez and Garcia 1992b). Most of the chemical parameters except lignin content and CEC decreased over time with the major reduction experienced during the active phase or biooxidative stage when the more readily available organic compounds are decomposed. For example, Jimenez and Garcia (1991) observed 20% and 33% total organic matter (TOM) losses in the bio-oxidation phase of composting urban refuse (pile R) and urban refuse and sewage sludge mixture (pile R+S). The TOM losses over the full composting period were 29% for pile R and 42% for pile R+S. The higher TOM loss in pile R+S was attributed to the significant metabolic rate observed during the first few days of composting, because of the abundance of indigenous microorganisms in the urban refuse-sewage sludge mixture and the high specific area exposed to biological oxidation (Jimenez and Garcia 1991).

Jimenez and Garcia (1992a) suggested the oxidizable carbon content is a more interesting parameter than TOM, because it shows the oxidation state and hence the chemical stability of the carbon. The oxidizable carbon content of the mixture of city refuse and sewage sludge decreased throughout the composting process.

Riffaldi *et al.* (1986) observed changes in hemicellulose and cellulose phenols, lignin, total nitrogen, hydrolysable nitrogen, nitrate, and ammonium in a compost mixture of paper processing wastewater sludge and straw. Hemicellulose and cellulose decreased by 20 and 40% of organic matter in the first 60 days providing evidence for the fact that chemical constituents of organic matter have different decomposition rates. Riffaldi *et al.* (1986) also found the phenol content (as percentage of organic matter) decreased

rapidly for the first 2 months and then levelled off. The lignin content increased almost linearly to about 50% of organic matter and then increased at a more gradual rate.

Riffaldi *et al.* (1986) observed the total nitrogen content for their compost mixtures increased by about 30% in the first 30 days and then levelled off. After an initial increase, the ammonium content of the compost decreased throughout the composting process to a final value of about 15% of the initial nitrogen. The nitrate content increased by a factor of two. Riffaldi *et al.* (1986) felt that the total nitrogen, ammonium and nitrate content are useful parameters for estimating the degree of compost maturity. Although there are no absolute compost maturity values for the chemical parameters described above, the relative changes in these values can provide information regarding the degree of degradation.

Several authors have suggested the cation-exchange capacity (CEC) as a useful indicator of compost maturity (Riffaldi *et al.* 1986; Harada and Inoko 1980a; Harada and Inoko 1980b; Jacas *et al.* 1987; Jimenez and Garcia 1989; Jimenez and Garcia 1991; Jimenez and Garcia 1992a; Jimenez and Garcia 1992b). Harada and Inoko (1980) proposed a simplified method of determining the CEC capacity of composts as a practical measure to determine the degree of maturity of various composts. They found the CEC values of city refuse composts increased throughout the composting process and at maturation were greater than 60 meq/100 grams on an ash free basis. Jimenez and Garcia (1992a) noted that optimal values of the CEC for city refuse composts were greater than 67 meq/100 grams (ash free basis). They also indicated that a CEC/total carbon ratio value higher than 1.9 (meq/g carbon) may be considered a good maturity parameter.

2.6.3.2 Degree of Humification

Changes in the organic matter content of humic substances and their fractions in composts are also proposed to evaluate the composting process. Parameters such as the ratio of humic-acid-like carbon to fulvic-acid-like carbon (C_{ha}/C_{fa}), % humic acid, humification index (HI) and humification ratio (HR) were considered

by several authors as compost maturity indices (Riffaldi *et al.* 1986; More and Sana 1987; Saviozzi *et al.* 1988; Inbar *et al.* 1990; Jimenez and Garcia 1992a; Jimenez and Garcia 1992b; Chen and Inbar 1992. The extraction methods and parameter definitions seem to vary from author to author. The paragraphs below present the findings of a few selected authors.

Raw organic materials generally have low concentrations of humic acid and high levels of the fulvic fraction (Inbar *et al.* 1990). As the composting process proceeds the humic acid fraction increases and the fulvic acid fraction decreases (Jimenez and Garcia 1992a). Jimenez and Garcia (1992a) observed that the ratio of humic acid-like carbon to fulvic acid-like carbon (C_{ha}/C_{fa}) increased during the composting of city refuse and a mixture of city refuse and sewage sludge due to the formation of polycondensed substances. They indicated a value of C_{ha}/C_{fa} ratio higher than 1.9 may be considered be a good indicator of compost maturity for composts of municipal solid waste and sewage sludge. The humification ratio (HR) as defined by (C_{ha}+ C_{fa})*100/organic carbon content did not vary during the composting process and therefore is not considered a suitable maturity index (Jimenez and Garcia 1992a). Saviozzi *et al.* (1988) observed the humification index, defined as the ratio of the organic carbon of the nonhumified fraction to humus carbon decreased for composts of refuse and farm yard manure. They indicated this parameter has potential as a maturity indicator but that further tests on a greater number of wastes were required.

2.6.3.3 Water Extracts

A number of authors have studied the changes in chemical components of compost water extracts and proposed maturity parameters such as organic carbon/ organic nitrogen ratio ($C:N_w$), and water soluble carbon/ water soluble nitrogen ratio (WSC/WSN) as reliable and absolute indicators of compost maturity (Chanyasak *et al.* 1980; Chanyasak and Kubota 1981; Chanyasak *et al.* 1982; Chanyasak *et al.* 1983; Hirai *et al.* 1983; Levi-Minzi *et al.* 1986; Saviozzi *et al.* 1987; Riffaldi *et al.* 1988; Garcia *et al.* 1991a; Garcia

et al. 1991b). The following paragraphs explain the rationalization of monitoring the changes in compost water extracts, describes the trends in chemical parameters observed by various authors, and provides absolute values for key maturity indicators.

Chanyasak *et al.* (1982) rationalized the usefulness of monitoring changes of soluble components in water extracts by noting the composting reaction is a biochemical decomposition of the organic matter in materials by microorganisms whose metabolism occurs in the water soluble phase. Simple low molecular weight compounds soluble in water such as sugars and organic acids are easily assimilated by microorganisms. Large-molecular-weight polymers in organic materials are mostly water insoluble and must be broken down before they can be utilized (Mathur *et al.* 1992). Microorganisms excrete extracellular enzymes into solution which hydrolyse the long chain polymers into simpler compounds. Thus the changes in the chemical components in the water soluble phase versus the solid phase better represent the degree of maturity of the compost.

Chanyasak *et al.* (1980) observed changes over time in TOC, low fatty acids, amino acids, polysaccharides and peptides for a compost mixture of sewage sludge and rice husks. They found the TOC decreased by 31% throughout the composting process with the major decrease due to the reduction of amino acids and low fatty acids. Low-molecular-weight polysaccharides and peptide compounds also decreased and the higher molecular weight compounds made up a large portion of the polysaccharides and peptides in the final compost product.

Saviozzi *et al.* (1986) observed changes in dry matter, organic carbon, nitrogen, volatile acids, and amino acids for a compost mixture of waste water sludge from a paper processing plant and chopped straw. They found the water soluble components initially increased during the first five days and then followed a gradual decreasing trend throughout the remainder of the 120 day composting period. The initial increase was attributed to the increasing rate of decomposition by the microorganisms. Saviozzi *et al.* (1986) suggested the hydrolysis and solubilization of the

complex substances initially predominated over mineralization and immobilization processes. The final dry matter, organic carbon and nitrogen values were 15%, 20% and 40%, respectively of the initial values. The amino acids and volatile acids also decreased during the composting period. The volatile acid content decreased to 50% of the initial value. Most of the tested chemical parameters however did not reach an equilibrium value after 120 days.

Garcia *et al.* (1991a) monitored the water soluble carbon, sugar content, total and organic nitrogen, nitrate, and ammonium concentration for compost mixtures of aerobic sludge, city refuse, peat residue and grape debris. They observed a decrease in water soluble carbon with time in all mixtures indicating the process of minerlization was more dominant than the process of hydrolysis and solubilization. Total and organic nitrogen decreased during the composting process with the largest losses observed during the bio-oxidative phase. Ammonium content also decreased with time. Garcia *et al.* (1991b) indicated that the total, organic and nitrate nitrogen cannot be considered as suitable indices of compost maturity because the final values are dependent on the original organic materials.

Chanyasak and Kubota (1981) proposed the ratio of water soluble organic carbon to organic nitrogen ($C:N_W$) as an essential indicator of compost maturity. They found the $C:N_W$ ratio for well-matured composts of different materials were almost always between 5 to 6. Garcia *et al.* (1991b) observed the organic carbon to organic nitrogen ratio decreased throughout the composting process with final values being less than 5.

Additional water extract maturity parameters proposed in the literature include water soluble carbon/water soluble nitrogen ratio (WSC/WSN), water soluble organic matter content (WSOM), sugar content and a biodegradability index. Garcia *et al.* (1991b) found the WSC/WSN ratio decreased considerably in all their compost mixtures to final values less than 2. The final values of water soluble organic matter were less than 2.2 g/liter at the end of maturity. They also indicated a soluble sugar content of less than 0.10% in compost extracts can serve as a suitable maturity

indicator. Morel *et al.* (1979) proposed a biodegradability index based on TOC, and soluble sugar content of water extracts and the age of the compost. The equation is shown below.

$$ID = 3.166 - (0.011\ AGE) + (0.059\ TOC) + (0.832\ pHs) \quad (2)$$

ID = Index of degradability
AGE = Days of maturation
TOC = total organic carbon content
pHs = Hot-water-soluble sugar content

ID values of composts less than 2.4 are considered mature. Garcia *et al.* (1991b) noted the ID values in their tests were less than 2.4 after maturation, therefore they supported the use of the index of degradability to evaluate the maturity of composts.

2.6.4 Physical Tests and Spectroscopy

Some physical tests such as pile temperature, colour and particle size are used as secondary parameters to provide indications of compost maturity. The temperature increases in the first few days of the process, remains between 60 and 70^{0}C for a period of time and then decreases during the cooling stage and finally reaches a constant temperature during the maturation phase (Golueke 1972).

The colour of refuse compost darkens as the process progresses (Jimenez and Garcia 1989). Sugahara and Inoko (1981) proposed a technique to assess the degree of darkness of composts using the relative spectral reflectance of compost measured in a colour analyser.

Penninck and Verdonck (1987) observed that the particle size of pine bark compost decreased throughout the process. They also found a linear relationship exists between oxygen consumption and the decrease in particle size distribution sum.

In contrast to the simple tests discussed above, some authors have used more sophisticated methods such as; solid state ^{13}C nuclear magnetic resonance spectroscopy and infrared spectroscopy. (Inbar and Chen 1992). Due to limitations in expertise and resources,

these methods were not considered when selecting maturity indicators for this research.

2.6.5 Maturity Selection Criteria

Evaluation of compost maturity has long been recognized as one of the more important problems encountered in composting (Riffaldi *et al.* 1986). Resource and operational constraints often impact the selection of maturity parameters. Outlined below is a brief list of criteria to be considered when selecting maturity tests:

1) simplicity of test
2) costs
3) reliability
4) duration
5) correlation with other parameters

Based on the criteria above, tests including OUR, changes in organic matter (%carbon), water extract analyses (TOC, $C:N_W$), CEC, and bioassays should be strongly considered as indices of compost maturity.

2.6.6 Section Review

Compost maturity, which serves as an indicator of process performance and product quality has been defined as the degree of decomposition of organic matter during composting. No single test has been found to indicate maturity for all composts; therefore, a series of parameters are usually measured. The various methods proposed may be grouped into five categories: plant bioassays, microbial bioassays, chemical analyses, physical tests and spectroscopy. Many of the tests require monitoring changes in properties of the compost from the beginning of the process to the point of stabilization. Some of the more frequently utilized maturity tests are seed germination or plant growth tests, respiration rate of the compost, changes in organic matter, cation exchange capacity, humification ratios and the change in organic matter and organic carbon /organic nitrogen ratio ($C:N_w$) in compost water extracts. Summary information of the frequently used tests is outlined in the following paragraph.

Plant bioassays are perhaps the most reliable and the ultimate test to indicate compost maturity. Seed germination tests are used to evaluate the phytotoxicity of compost water extracts. Reported germination index values vary from 35% to over 80 to 85% depending upon the organic material being composted. Respiration methods are a good test of compost stability, but no standard method has been adopted and the oxygen uptake rate (OUR) must be determined throughout the composting process. The OUR decreases as the age and stability of the compost increases. Many chemical analyses that monitor the change in organic matter and its constituents throughout the composting process can provide information regarding the degree of degradation but again there are no absolute compost maturity values for these chemical parameters. The cation exchange capacity (CEC) has been suggested as a useful indicator of compost maturity. Researchers have observed the CEC values of city refuse composts increase throughout the composting process and at maturation were greater than 60 milliequivalent /100 grams on an ash free basis. More tests involving different organic materials are

required to verify the usefulness of the CEC parameter. Changes in the organic matter content of humic substances and their fractions in composts are also proposed to evaluate the composting process. As the composting process proceeds, the humic acid fraction of compost increases and the fulvic acid fraction decreases. Parameters such as the ratio of humic-acid-like carbon to fulvic-acid-like carbon (C_{ha}/C_{fa}), and humification index (HI) are considered by several authors as compost maturity indices. A value of C_{ha}/C_{fa} ratio higher than 1.9 has been suggested as a good indicator of compost maturity for composts of municipal solid waste and sewage sludge. Compost water extract analyses have been indicated as useful compost maturity parameters because composting involves the biochemical decomposition of the organic matter in materials by microorganisms whose metabolism occurs in the water soluble phase. Monitoring the change in water extract chemical parameters throughout the composting process such as TOC, dry matter, organic carbon, polysaccharides and nitrogen compounds provide an indication of compost maturity but again are not considered absolute indicators. The $C:N_w$ ratio, water soluble carbon/water soluble nitrogen ratio (WSC/WSN), and water soluble organic matter content are considered essential indicators of compost maturity. The final $C:N_w$ ratio for well matured composts of different materials were observed to be almost always between 5 to 6. Garcia *et al.* (1991b) found the WSC/WSN ratio decreased considerably in all their compost mixtures to final values less than 2 and the final values of water soluble organic matter were less than 2.2 g/liter at the end of maturity. Morel *et al.* (1979) proposed a biodegradability index to indicate compost maturity. Biodegradability index values of composts less than 2.4 were considered mature. Finally, more sophisticated methods such as; solid state ^{13}C nuclear magnetic resonance spectroscopy and infrared spectroscopy have been used to evaluate compost maturity but due to limitations in expertise and resources, these methods were not considered when selecting maturity indicators for this research.

2.7 Decomposition Models

This section of the report discusses the importance of compost kinetics and reviews a few models of the composting process proposed in literature. Kinetics involves the rate or speed of a reaction or process. The purpose of modelling the decomposition of organic wastes is to evaluate the biological degradation of these materials over time and provide a tool for optimization of the process. Due to the complexity of the multi-step composting process, the development of mathematical models is very difficult. The effects of environmental rate-limiting factors also add to the complexity of modelling the decomposition process.

There are few studies on the kinetics of composting existing in literature and most deal with reactor vessel applications. Some studies involve the solving of a series of interrelated equations, while others provide a first order reaction rate constant for the decomposition process. Haug (1980) and Whang and Meenaghan (1981) proposed first order rate models similar to the Michaelis-Menten equation for enzyme-substrate complex kinetics. Keener *et al.* (1992) developed a first order model based on the rate of disappearance of compost mass. Finger *et al.* (1976), and Nakasaki *et al.* (1987) modelled the composting process by using heat and mass balance equations. Hamelers (1992) proposed the Composting Particle Kinetics (CPK) model which deals with the composting process at the substrate particle level.

The biological decomposition of plant residues in soils has also been described by first order kinetics. Multicomponent first order rate equations have been developed for the decomposition of plant residues such as straw (Cheshire *et al.* 1979; Paul and Clark 1989; Murayama *et al.* 1990). The following sections review the existing composting kinetic models and then the multicomponent equations for decomposition of organic materials in soils.

2.7.1 First Order Models: Michaelis-Menten Type

The composting process involves a sequence of complex steps.and any one of the steps can be rate-limiting (Haug 1980). The breakdown and solubilization of complex organics compounds into simpler compounds is an important step in the overall process. This step involves the enzyme-catalyzed hydrolysis of the complex organic substrates. Haug (1980) and Whang and Meenaghan (1981) proposed first order rate models for the decomposition process based on the Michaelis-Menten equation for enzyme-substrate kinetics. The overall equilibrium equation for the enzyme substrate reaction is shown below (Voet and Voet 1990).

$$E_f + S \rightleftharpoons ES \longrightarrow P + E_f \qquad (3)$$

E_f = free enzyme
S = substrate
ES = enzyme-substrate complex
P = products
k_1 = reaction rate for the formation of ES
k_{-1} = reaction rate for disassociation of ES to the original constituents E_f and S
k_2 = rate constant for the formation of the original enzyme and desired product P.

While Whang and Meenaghan (1981) based their model on the Michaelis-Menten equation, they used the variable **X** for free microorganism instead of **E** for free enzyme. They are probably suggesting the concentration of enzymes is dependent upon the concentration of microorganisms. Haug (1980) used the variable **a** to represent a vacant site on the substrate surface instead of the variable **S** for substrate.

Haug (1980) classified the composting of organic residues as being a heterogeneous system consisting of particulate substrate limited to bound water. He first presented the model shown below for the kinetics of the solubilization of solid substrate particles.

$$\frac{ds}{dt} = v = \frac{(k_2\, a_0\, e_0)}{(K_a + e_0)} \qquad (4)$$

v = product formation/unit time

a_0 = the total number of adsorption sites on substrate surface per unit volume

e = the number of free enzymes per unit volume of the reaction mix.

k_2 = rate constant for the formation of the original enzyme and desired product **P**

$K_a = \frac{k_{-1} + k_2}{k_1}$

The rate of product formation or disappearance of solid substrate is a function of the number of enzymes per unit volume and the total number of adsorption sites on the substrate surface per unit volume. As the number of enzymes increase, the rate of product formation increases. At high enzyme concentrations, the available adsorption sites are occupied and the rate of reaction would be at its maximum (Haug 1980). Haug (1980) indicated that researchers have found this equation successfully represents the kinetics of the enzyme-substrate system.

Haug (1980) adapted the model described above to include **X**, the mass concentration of microbes. In developing this equation, he theorized the concentration of enzymes is a function of the microbial concentration and the total number of adsorption sites is likely related to the available substrate surface area per unit volume. The proposed model is described below.

$$-\frac{ds}{dt} = \frac{k A_V X}{K_X + X} \qquad (5)$$

ds/dt = rate of hydrolysis of solid substrate
k = maximum rate of hydrolysis occurring at high microbial population.
A_V = Available surface area (substrate) per unit volume.
K_X = half velocity coefficient. (The microbial concentration at 1/2 the maximum reaction rate.)

The rate of hydrolysis is a function of the size of the microbial population **X**, and the available substrate surface area per unit volume **A_V**.
The equation above can simplified for two general cases;

Case 1 $X \ll K_X$ $\quad \frac{ds}{dt} = -k'A_V X$ (6)

Case 2 $X \gg K_X$ $\quad \frac{ds}{dt} = -kA_V$ (7)

$k' = k/K_X$

Case 1 When the concentration of microbes is much less than **K_X** the rate of hydrolysis of the solid substrate is a first order reaction with respect to the microbial concentration. The reaction rate will increase with the increasing concentration of microbes. As the microbial population expands beyond **K_X**, the rate of hydrolysis approaches a maximum.

Case 2 When the microbial concentration is much greater than the 1/2 velocity constant K_X, the change in solid substrate over time is a function of the available substrate surface area per unit volume A_V. It is a zero order reaction with respect to microbial concentration. The reaction rate is at its maximum and an increase in the microbial population will not result in a increase in reaction rate.

Haug (1980) indicated the model presented above has not been experimentally verified. However, it can be used to explain several phenomena observed in actual composting operations. He suggested the different decomposition rates observed for different materials can probably be explained by different kA_V values. Materials such as wood, which are more resistant to decomposition, probably have lower values of kA_V than wastes which are more amenable to solubilization. Haug (1980) explained this could also be interpreted as a lower number of available enzyme binding sites on the substrate, or a lower number of successful enzyme reactions in the more resistant materials.

A mixture of organic materials in a composting windrow will have different kA_V values. Organic materials with high kA_V values decompose during the early stages of the process, while the more resistant materials decompose at a lower rate over a longer period of time (Haug 1980).

Haug (1993) indicated once the solid substrate has been solubilized the Monod kinetic model can be used to represent the rate of substrate utilization. The Monod model is presented below (Haug 1993).

$$\frac{dS}{dt} = - \frac{k_m S X}{K_s + X} \qquad (8)$$

dS/dt = rate of substrate utilization, (mass per volume time)

X = concentration of microbes, mass/volume

k_m = maximum utilization coefficient, maximum rate of substrate utilization at high substrate concentration (mass substrate/mass microbes-day)

S = concentration of rate limiting substrate, mass/volume

K_s = half velocity coefficient (mass/volume)

The rate of consumption of substrate is a function of the microbial and substrate concentrations. The Monod model can be further defined by two general cases which are similar to the cases defined in the Whang and Meenaghan (1981) model.

The model presented by Whang and Meenaghan (1981) is the same mathematical equation proposed by Monod for the rate of substrate utilization. The equation is shown below.

$$R = \frac{K_2 C}{K_1 + C} \qquad (9)$$

R = consumption rate of substrate which is equal to the production rate of products.

X_T = the total microorganism concentration.

C = substrate concentration

K_1 = $\frac{k_{-1} + k_2}{k_1}$

K_2 = $k_2 X_T$

k_2 = rate constant for the formation of the original enzyme and desired product P.

The rate of consumption of substrate is a function of the microbial and substrate concentrations. Whang and Meenaghan (1981) did not specify units for the terms in their model presented above. Again the model can be further defined by two general cases.

$$\textbf{Case 1} \quad S << K_1 \quad \frac{ds}{dt} = \frac{k_2 X_T C}{K_1} \tag{10}$$

$$\textbf{Case 2} \quad S >> K_1 \quad \frac{ds}{dt} = k_2 X_T \tag{11}$$

Case 1 When the substrate concentration is much less than K_1, the rate of consumption increases as the substrate concentration increases. The rate of waste utilization is described by a first order reaction with respect to substrate.

Case 2 When the substrate concentration is much greater than K_1, the enzymes are saturated with substrate and the rate of consumption is at its maximum. This is a zero order reaction with respect to substrate.

Whang and Meenaghan (1981) tested their model under experimental conditions with a small pilot plant. The compostable raw material was cattle manure. Their values for the kinetic constants are listed in the Table 2.5 found below.

Table - 2.5
Kinetic Constants of the Whang and Meenaghan Model

Kinetic Constants	Experiment Number		
	4	5	6
K_1, $\frac{\text{g Carbon}}{\text{g Ash}}$	1.0623	1.1362	1.2243
K_2, $\frac{\text{g Carbon}}{\text{g Ash-Day}}$	0.0113	0.0325	0.0292

The values for K_1 were consistent. This led Whang and Meenaghan (1981) to propose that K_1 is a general characteristic system parameter. Their values of K_2 varied considerably and they suggested this is a function of the experimental conditions. Based on the proposed model, K_2 is directly proportional to the rate of consumption and any increase in K_2, will result in an increase in the rate Whang and Meenaghan (1981).

2.7.2 First Order Model - Change in Compost Mass

Keener *et al.* (1992) developed a first order rate equation for the rate of disappearance of compost mass during the second phase of the composting process. This stage is characterized by the decomposition of the readily available organic substrates. As the composting process enters the curing stage, the rate of decomposition decreases and the rate of disappearance of compost mass deviates from the model (Marugg *et al.* 1993). The equation for the first order model is shown below.

$$\frac{dm(t)}{dt} = -k\,(m(t) - m_e) \qquad (12)$$

$m(t)$ = mass (kg) of composting material (dry basis) at time t.

t = time in days.

m_e = equilibrium mass (Kg), nondigestable (dry basis).

k = reaction rate.

$m_e = \beta m_0$

m_0 = initial dry matter (kg)

β = compost equilibrium value (me/m_0)

The rate of disappearance of the compost mass is a function of compost mass at time **t** and the term equilibrium mass (m_e). Keener *et al.* (1992) assumed the decomposition of the initial dry matter m_0 reaches an equilibrium value during the process. The equilibrium mass is determined by multiplying the initial dry matter mass by the equilibrium value **ß**. The equilibrium value is the fraction of the

materials which remain after a long period of complete composting (six months to a year) (Keener *et al.* 1992).

Keener *et al.* (1992) assumed a constant reaction rate **k** and presented a solution to their model as well as introduced the term compost mass ratio (**mR**). The solution is presented below.

$$mR(t) = \frac{m(t) - m_e}{m_0 - m_e} = e^{-kt} \qquad (13)$$

The compost mass ratio is a dimensionless number that provides an indication of how far the composting process has proceeded (Keener *et al.* 1992).

Keener *et al.* (1992) and Marugg *et al.* (1993) carried out tests with vessel type reactors to test the validity of the first order reaction model. When the ß value is known, the reaction rate is calculated from the model equation by determining the equilibrium mass and the change in mass over time. For composting of a mixture of wastes, the overall equilibrium value is calculated from the equation presented below, provided the constituent data is available (Marugg *et al.* 1993).

$$ß = \sum ß_{ei} w_i \qquad (14)$$

$ß_{ei}$ = compost equilibrium value (kg/kg) for each constituent

w_i = dry weight fraction for each constituent i.

i = constituent (examples: cellulose,hemicellulose, ash)

Table 2.6 lists compost equilibrium values for various mixtures.

Table - 2.6
Compost Equilibrium values for different mixtures
Marugg et al. (1993)

Materials	**ß %**
Grass clippings	17
Brush	70
Leaves	75
Cardboard	40
Low grass/ leaf mixture	61
High grass/ leaf mixture	46
High grass/ cardboard mixture	40

If the ß value is not known the the reaction rate and ß value can be evaluated from the decomposition curve (Keener *et al.* 1992). The decomposition rate constant can be determined by calculating the slope of the curve. Using equation 13 the value of m_e and hence the ß value can then be determined.

The reaction rate k is influenced by several factors including moisture content, temperature and particle size (Marugg *et al.* 1993) Marugg *et al.* (1993) maintained an optimum moisture content, but applied a temperature correction to their reaction rate constants, because of the difficulty in controlling the temperature. The temperatures in the compost vessels varied from 35 ^{0}C to 60 ^{0}C throughout the process. The temperature correction is calculated using the equation proposed by Schultz (1962). It is shown below.

$$\textbf{Temperature Correction} = \frac{1.066^T}{46.28} \qquad (15)$$

Marugg *et al.* (1993) recognized that the average particle size in their pilot tests was small compared to full scale vessel composting operations therefore, the rate constants may be different.

Keener *et al.* (1992) discussed the results of an evaluation of the reaction rate for the composting of poultry manure and corncobs. Based on the k value of 0.048/day for the first three days, the model predicted that only 8.4 days are required to reach the mR value

measured on the 14th day of composting. The deviation from the measured curve is probably due to changes in chemical composition of biomass, drying out of the biomass and the availability of the substrate to the microorganisms (Keener *et al.* 1992).

Marugg *et al.* (1993) composted mixtures of grass, leaves and cardboard and determined the reaction rate constants for the Keener *et al.* (1992) kinetic model. The active composting stage is approximately one month with a two to three month curing stage. The reaction rate constants for the different compost mixtures were found to be significantly different but the mR ratios approached the same values. Table 2.7 adapted from Keener *et al.* (1992) summarizes the decomposition rates (k) for Marugg *et al.* (1993) as well as some reaction rate constants determined by other researchers. Other researchers used different means such as the change in volatile solids over time or oxygen consumption rate to determine the reaction rate constant (k).

Table - 2.7
Decomposition Rate for Various Compostable Materials

Materials	k kg/kg-day	Reference
Sludge-primary	0.025	Shell & Boyd in Haug(1980)
Straw	0.069	Carlyle in Finstein(1986)
Maple leaves	0.015	Finstein(1986)
Oak leaves	0.009	Finstein(1986)
Cage manure/corncobs	0.048	Keener (1991) in Keener(1992)
Low grass/leaves	0.190	Marugg (1993)
	0.167	Marugg (1993)
High grass/cardboard	0.179	Marugg (1993)
	0.165	Marugg (1993)

2.7.3 Other Composting Kinetics Studies

Some researchers have modelled the composting process in reactor vessels by solving a series of heat and mass balance equations (Finger *et al.* 1976; Nakasaki *et al.* 1987). Nakasaki *et al.* (1987) predicted the rate of evolution of carbon dioxide, volatile matter conversion, and changes in compost temperature and moisture content. They found their predicted results compared favourably with experimental and commercial-scale measurements.

Hamelers (1992) expressed concerns with the use of empirical kinetic equations and the use of microbial kinetics to describe the composting process. First, he indicated the empirical equations were useful for optimizing the process only within the region of validity of the equations. Secondly, he stated it was impossible to use microbial kinetics to describe the composting process.

Hamelers (1992) proposed the Composting Particle Kinetics (CPK) theoretical model which deals with the composting process at the substrate particle level. The waste particle system included complex organic matter, monomeric organic matter, biomass, oxygen and water. To simplify the model, organic substrate are classified

into two groups; insoluble polymeric or soluble monomeric and the biomass was considered as one group.

The complex mathematical CPK model was based on equations of the main steps of the composting process at the particle level including; the hydrolysis of polymeric substrate, oxidation of monomeric substrate, decay of biomass, transport processes for oxygen, and monomeric substrates. By numerically solving a set of differential equations and one equality relationship, the model was used to predict the oxygen uptake rate of a organic waste.

2.7.4 Decomposition of Plant Residues

The decomposition rate of plant residues in soils has also been experimently found to follow first order rate kinetics (Paul and Clark 1989). Some researchers have found the decomposition of plant residues such as straw is best represented by a double component exponential decay expression (Murayama *et al.* 1990; Cheshire *et al.* 1979). The equation presented by Murayama *et al.* (1990) is shown below.

$$Y_t = C_1 \exp(-k_1 t) + C_2 \exp(-k_2 t) \qquad (16)$$

Y_t = amount of residues remaining at time t
C_1 = initial proportion of labile fraction
C_2 = initial proportion of non-labile fraction
t = time

The equation indicates that different fractions of the plant residue decompose at different rates. The reaction rate of the easily decomposable fraction is higher than the more resistant fraction of the plant residue.

Paul and Clark (1989) cited a model by Van Veen *et al.* (1984) for the decomposition of complex substrate such as crop residue. Complex organic matter such as straw can be divided into three fractions: easily decomposable sugars and amino acids, slowly decomposable cellulose and hemicellulose and, finally, resistant lignin. The reaction rates of the component fractions are different

and are characteristic of the type of organic material undergoing decomposition. The equation developed for the decomposition of straw under laboratory conditions and the numerical results are shown below.

$$A = C_1 \exp(-k_1 t) + C_2 \exp(-k_2 t) + C_2 \exp(-k_3 t) \quad (17)$$

$$100 = 15 \exp(-0.2t) + 65 \exp(-0.08t) + 20 \exp(-0.01t)$$

A = amount of residues remaining at time t

C_1 = actual plant carbon-C remaining as proteins and solubles

C_2 = actual plant carbon-C remaining as cellulose and hemicellulose

C_3 = lignin

t = time

The equation shows the the initial carbon content of each component and the reaction rates after correcting for microbial population. As expected, the more easily decomposable organic fractions have higher reaction rates than the more resistant lignin. The amount of total carbon remaining in the soil includes not only the amount of carbon in the plant residues and the intermediate products, but also the carbon content of the microbes. In order to determine the actual decomposition rate of the plant residue components the carbon content of the microbes must be subtracted. The change in the total % carbon remaining in the soil over time does not accurately represent the decomposition of plant residue in soils.

This brief summary of the decomposition of plant residues in soils is not meant to be a complete summary of this topic, but a brief discussion highlighting that the decomposition process has been successfully represented by first order kinetics and that different fractions of the organic material have different reaction rates.

2.8 Section Summary

In summary, there are very few studies available in the literature on composting kinetics and most, if not all, are reactor vessel applications. Some studies involved solving a series of interrelated equations, while others provide a first order reaction rate constant for the decomposition process. Haug (1980) and Whang and Meenaghan (1981) proposed first order rate models similar to the Michaelis-Menten equation for enzyme-substrate complex kinetics. Keener *et al.* (1992) developed a first order rate equation for the rate of disappearance of compost mass during the second phase of the composting process. The decomposition of plant residues in soils has been experimently found to follow first order rate kinetics (Paul and Clark 1989).

Despite the complexity of the composting process, evaluating the overall reaction rate and reviewing physical models can be useful to engineers and others in terms of understanding the process and potentially identifying opportunities for optimization. Measuring the change in substrate concentration, mass and OUR over time can be used to determine the overall decomposition rate. As previously stated, the change in % carbon, TOC (water extracts), oxidizable carbon are some of the parameters measured to represent the change in substrate concentration.

The observed decomposition rates can also be compared to some of the existing kinetic models. In a windrow type composting experiment measuring the change in mass over time is not practical. Therfore the model developed by Keener *et al.* (1992) model will not be considered. Comparing the observed decomposition rates to the physical model proposed by Haug (1980) appears to have the most merit; given that this research involves a field experiment and not a highly controlled composting vessel study.

2.9 Summary and Hypotheses

In this chapter the basic theory of composting is reviewed including the process principles and rate limiting factors, measures of the degree of decomposition or maturity and various decomposition models.

Composting was defined as a bio-oxidative process that: 1) involves a heterogeneous organic substrate in the solid state; 2) evolves by passing through a thermophilic phase and a temporary release of phytotoxin; and 3) leads to production of carbon dioxide, water, minerals and stabilized organic matter (Zucconi and de Bertoldi 1987).

Composting systems can be divided into reactor and non-reactor systems and the chemical components of compostable organic materials can be divided into three main fractions: carbohydrates, lignin, and nitrogen compounds. The decomposition and stabilization of organic materials is brought about mainly by the activities of three main microbial groups bacteria, fungi and actinomycetes.

Composting is a dynamic and very complex process involving many steps including the the microbial release of enzymes, hydrolysis of polymeric substrates, transport and diffusion of substrate and oxygen, and the oxidation of the substrate by biochemical reactions. Environmental factors; nutrient concentration and availability, moisture, oxygen concentration, temperature, and pH level which influence the composting process mainly by affecting the rate of growth and degree of microbial activity.

The determination of compost maturity is very difficult and no single test has been found to indicate maturity for all composts therefore a series of parameters are usually measured.

There are few studies on the kinetics of composting existing in literature and most deal with reactor vessel applications. Haug (1980) and Whang and Meenaghan (1981) and Keener *et al.* (1992) proposed first order rate models similar to the Michaelis-Menten equation for enzyme-substrate complex kinetics. The decomposition of plant residues in soils has been found to follow first order rate

kinetics. Based on what has been presented in the literature several hypotheses can be made regarding the optimization of the composting process.

Hypotheses

1) A high moisture content (50 to 65 %) during the mesophilic and thermophilic and cooling phases of the composting process increases the decomposition rate. A high moisture level is required during the initial decomposition stages as the more easily decomposed substrates are utilized resulting in rapid growth of the bacterial population and an increase in temperature of the compost mass. The increase in temperature of the compost pile will result in moisture losses due to evaporation. Moisture content requirements are lower during the maturation stage when the fungi and actinomycetes prevail (Zucconi and de Bertoldi 1987).

2) Increasing of the C/N ratio of yard waste by the addition of straw increases the decomposition rate. The C:N ratio of freshly mowed grass is approximately 12:1 to 15:1 which is below the optimum C:N ratio range of 19:1 to 30:1. At the lower C:N ratio level, there is an excess of nitrogen and ammonia volatilizes to the atmosphere and the pH level may rise to inhibitory levels. Golueke and Diaz (1990) also suggested an excess of ammonia may be toxic to some microbes. By adding straw which has C:N ratio values ranging from approximately 50:1 to 150:1 the C:N value of the mixture can be increased to within the optimum range.

3) The addition of wood chips to increase the porosity during the cooling phase of composting increases the decomposition rate. As the composting process proceeds the particle size of the material decreases resulting in a decrease in porosity. By adding additional wood chips during the cooling stage, the porosity of the compost mass should increase providing more ventilation and hence oxygen availability. There appears to be no specifc porosity value recommended to optimize the decomposition process. Schulze (1962) has stated a 30 % minimum free air space (FAS) should be maintained.

4) Building up the compost piles will result in higher pile temperatures during the cooler ambient conditions. The degradation of the organic materials, therefore, is not greatly reduced by the cold ambient temperatures. Large-size windrows tend to be self-insulating and heat losses are minimized. By retaining enough heat, higher compost temperatures are maintained which promotes the continued optimal decomposition of the organic materials. The optimum temperature range for the composting process is approximately between 45^0C to 55^0C.

3.0 EXPERIMENTAL DESIGN

The primary objective of this research was to systematically evaluate the influence of key operational variables on the decomposition rate of yard waste in a windrow composting system. A factorial design approach was selected to evaluate the influence of the operational variables because it is the most efficient method to estimate the effects of two or more factors and their interactions (Montgomery 1984). This experimental approach does not appear to have been previously used by researchers to investigate the effects of major rate limiting factors and their interactions on the decomposition of organic materials. Keener *et al.* (1993) investigated the effects of a number of controllable factors on the vessel-composting of poultry manure one variable at a time. They observed the reduction in compost mass, dry matter and nitrogen at two different levels for each controllable factor. Their research did not consider the collective effects of the other variables and interactions on the change of their response variables. The advantages of the factorial design include the requirement of fewer trials per factor studied, indication of major trends and providing a direction for further research. Factorial designs can also be easily incorporated into designs of larger experiments (Box *et al.* 1978). The following sections outline the factorial design approach for this research, and discuss the selection of operational variables, response variables and experimental levels. In addition, the factorial design matrices, pile descriptions and operational activities are outlined.

3.1 Factorial Design

A factorial design is an efficient and systematic method to evaluate the effects of factors and their interactions on a measured response. The investigator selects the factors to studied and establishes a high and low level for each variable. From the number of variables and levels, the number of trials or runs is determined. A 2^3 factorial design, for example, involves 3 variables at 2 different levels with a total of 8 trials. The factorial design investigates all possible combinations of the levels of the factors.

Replicate trials or runs are carried out to evaluate the standard deviation of the effects.

3.1.1 Operational Variables and Experimental Levels

Three operational variables; C:N ratio, moisture content and porosity adjustment (i.e., aeration) were selected as being the most important controllable factors influencing the decomposition of organic wastes. Other rate-limiting factors such as pile temperature and pH were not considered to be easily controllable or necessary to control. Windrow temperatures are extremely difficult if not impossible to control without forced aeration and, as indicated previously by Golueke (1972), adjusting the pH is expensive and may result in the loss of nitrogen due to the volatilzation of ammonia.

The first controllable factor C:N ratio has a optimum value of about 25 to 30 parts carbon to 1 part nitrogen for most compostable wastes (Golueke and Diaz 1990). The yard waste in our experiment consisted mainly of grass and some other plant matter. The C:N ratio of grass was approximately 12:1 to 15:1 which is well below the optimum and volatilization of ammonia will occur. To test the influence of the C:N ratio on the decomposition of organic wastes, three C:N ratio levels were established; low, medium and high. The low C:N ratio compost piles consisted of grass clippings with a C:N ratio of 12:1 while the medium and high C:N level piles were established by adding barley and wheat straw to the grass clippings to increase the C:N ratios.to approximately 20:1 and 30:1 respectively. The low C:N ratio piles served as a comparison to the city control piles C1 and C2. The control pile sections consisted mainly of grass and wood chips. The wood chips added to the piles to increase porosity were assumed not to contribute to the C/N ratio due to the their resistance to degradation.

The second variable, moisture content is very important to the degradation of organic wastes. As indicated previously, water is both a solvent and a medium for mass transfer of enzymes, nutrients, gases, and waste products within and outside the cell. Haug (1980) listed the optimum range of moisture content between

50 to 65% and Golueke (1977) indicated moisture levels below 50% limit microbial activity. In this experiment, the 60% moisture content was selected as the high level and 40% as the low level.

The last variable, porosity adjustment, represents the degree of aeration capability of the compost piles. Reinhart *et al.* (1991) found windrow turning provides only a limited amount of aeration and that the oxygen concentration quickly returns to previous levels. Turning the windrows does help break up and homogenize the materials. Convection represents the major method of aeration of simple windrow composting systems. Initially, wood chips were added to all piles to provide adequate void space and to allow for movement of air from the exterior environment into the interior of the pile. As the composting process proceeds, the organic materials are broken down and the particle and bulk densities of the compost increase, resulting in a decrease of void space and aeration capabilities. To increase porosity and aeration capabilities, additional wood chips were mixed into selected piles to evaluate the effect on the decomposition rate. The two levels of the qualitative variable porosity adjustment were initially-adjusted, and initially-adjusted and maintained. Table 3.1 summarizes the experimental levels of the operational variables.

Table 3.1 - Experimental Levels

Operational Factors	Minus Level	Middele Level	Plus Level
Initial C:N ratio	Low	Medium	High
Moisture Content	40%		60%
Porosity	Initially Adjusted		Initially Adjusted and maintained

3.1.2 Response Variables

Since no one parameter has been identified to clearly and independently indicate maturity, a series of parameters were selected to measure the rate of decomposition. Given the available resource constraints, the response parameters selected to measure the rate of decomposition are listed in Table 3.2.

Table 3.2 - Response Variables and Maturity Indicators

Reponse Variables	Maturity Indicators
% Decrease in Total Carbon (Solid samples)	C:Nw ratio
% Decrease in TOC (Water extracts)	OUR
% Increase in Dry Bulk Density	Compost Temperature

The selection is partially based on utilizing the chemical analyses performed to monitor the change in operational variables, therefore increasing the benefit of the work. The % decrease in TOC (water extracts) is considered the most reliable response variable chosen for this experiment, because aerobic decomposition of organic compounds involves the oxidation of the substrate within the organisms. The organic substrate must be water-soluble to enter the microbial cells. The $C:N_W$ ratio of compost water extracts and OUR were selected to indicate compost maturity. Compost pile temperature serves as a secondary, but not absolute maturity indicator.

3.1.3 Design Matrix

Using a -1 to represent the low level of each variable and a +1 to represent the high level and 0 to represent the middle level a design matrix describing the experimental runs can be developed. The -1, +1 and 0 coding can be used for both quantitative and qualitative levels of variables. Based on the 3 experimental levels for C:N ratio and 2 levels for moisture content and porosity, a total of 12 piles (3 x 2 x 2) were required for this research. Two replicate piles R1 and R2 were also developed to evaluate the pure error of the effects. The factorial design is displayed in Table 3.3.

The interactions between the variables are represented by the notations, 12, 13, 23 and 123. For example 12 represents the interaction between variable 1, C:N ratio and variable 2, moisture content. Piles 7, R1 and R2 are replicates for the factorial design.

Table 3.3 - Factorial Design Matrix - 1

Pile No.	Pile Designation	Variables			Interactions			
		C:N ratio	MC	Porosity				
		1	2	3	1 2	1 3	2 3	1 2 3
L 2	Low C:N, Low M.C., Low Por.	- 1	- 1	- 1	1	1	1	- 1
2	Hi C:N, Low M.C., Low Por.	1	- 1	- 1	- 1	- 1	1	1
L 1	Low C:N, Hi M.C., Low Por.	- 1	1	- 1	- 1	1	- 1	1
4	Hi C:N, Hi M.C., Low Por.	1	1	- 1	1	- 1	- 1	- 1
L 4	Low C:N, Low M.C., Hi Por.	- 1	- 1	1	1	- 1	- 1	1
6	Hi C:N, Low M.C., Hi Por.	1	- 1	1	- 1	1	- 1	- 1
L 3	Low C:N, Hi M.C., Hi Por.	- 1	1	1	- 1	- 1	1	- 1
8	Hi C:N, Hi M.C., Hi Por.	1	1	1	1	1	1	1
R 1	Med C:N, Hi M.C., Hi Por.	0	1	1	0	0	1	0
R 2	Med C:N, Hi M.C., Hi Por.	0	1	1	0	0	1	0
7	Med C:N, Hi M.C., Hi Por.	0	1	1	0	0	1	0
5	Med C:N, Low M.C., Hi Por.	0	1	1	0	0	1	0
1	Med C:N, Low M.C., Low Por.	0	1	- 1	0	0	- 1	0
3	Med C:N, Hi M.C., Low Por.	0	1	- 1	0	0	- 1	0

Through analytical techniques, the magnitude and significance of the effect of the variables called the main effects and their interactions can be estimated. The calculated main effect for a variable measures the average change in response over all conditions of the other variables (Box *et al.* 1978). The results of the factorial experiment should indicate which variables are significant and, directionally, how the variables and their interactions effect the response or performance variables.

To indicate whether an effect is significant, two methods are used. The first method involves determining the 95% confidence interval (CI) for each effect using a two sided t-test. The mean square of the residuals was used as an estimate of variance for the confidence interval calculations. An effect is considered significant if its 95% CI did not contain zero.

The second method for checking which effects are significant involves using a half normal plot. The absolute values of the effects are ranked from the lowest to highest values and a probability P_i is given by the equation shown below.

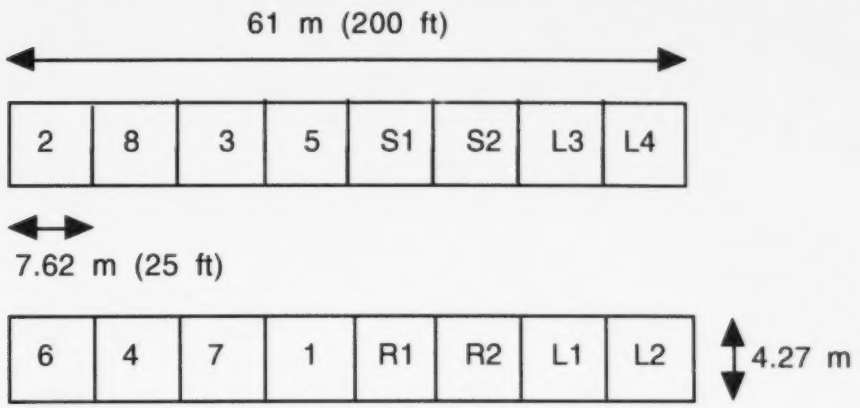
$$P_i = (i - 1/2)/n, \qquad i=1,2....,n. \qquad n = \text{number of effects}$$

The absolute values of the calculated effects are plotted on probability paper. The resulting line would be straight in the case of a null experiment. If any of the points deviate substantially from the straight line these effects are considered significant and are not easily explained as chance occurrences. Box *et al.* (1978) do not appear to provide guidelines on how much deviation is required to consider an effect significant.

3.1.4 Composting Process and Pile Descriptions

The windrow yard waste composting experiment was carried out at the City of Edmonton's Clear Bag program site located in the Roper Industrial area. Two large experimental windrows approximately 61m long, 4.3m wide and 1.8 high each containing 8 different pile sections were built according to the specifications of the experimental design, as outlined in Figure 3.1.

Figure 3.1 Compost Pile Sections Layout



Pile No. Pile Designations

1	Med C:N, Low M.C., Low Por.	**R 1**	Med C:N, Hi M.C., Hi Por.
2	Hi C:N, Low M.C., Low Por.	**R 2**	Med C:N, Hi M.C., Hi Por.
3	Med C:N, Hi M.C., Low Por.		
4	Hi C:N, Hi M.C., Low Por.	**L 1**	Low C:N, Hi M.C., Low Por.
5	Med C:N, Low M.C., Hi Por.	**L 2**	Low C:N, Low M.C., Low Por.
6	Hi C:N, Low M.C., Hi Por.	**L 3**	Low C:N, Hi M.C., Hi Por.
7	Med C:N, Hi M.C., Hi Por.	**L 4**	Low C:N, Low M.C., Hi Por.
8	Hi C:N, Hi M.C., Hi Por.		

S1 and S2 - Non Factorial Piles

Windrow **1** containing pile sections 6, 4, 7, 1, R1, R2, L1, and L2 was built on August 31, 1992. Windrow **2** containing pile sections 2, 8, 3, 5, L3, and L4 and other experimental piles was built on September 2, 1992. The pile sections were separated into 2 blocks, because two days were required to develop the various sections. The high C:N pile sections were placed at one end and the low C:N pile sections were placed at the other end of each windrow leaving the medium C:N sections in the middle of each windrow.

The response variables % change in carbon, total organic carbon of water extracts (TOC), bulk densities were used to identify differences in the experimental piles. Maturity parameters OUR, $C:N_w$ of compost water extracts and pile temperatures were measured to indicate the maturity of the compost in the respective pile sections. In addition, two control piles were selected from the City of Edmonton's windrows to serve as a comparison to the experimental piles. Pile descriptions for the various piles are shown in Table 3.4.

Table 3.4 - Pile Descriptions

Pile No.	Pile Designations	Operational Variables 1 C:N Ratio	2 Moisture Content	3 Porosity
1	Med C:N, Low M.C., Low Por.	Medium	40%	Initially adjusted
2	Hi C:N, Low M.C., Low Por.	High	40%	Initially adjusted
3	Med C:N, Hi M.C., Low Por.	Medium	60%	Initially adjusted
4	Hi C:N, Hi M.C., Low Por.	High	60%	Initially adjusted
5	Med C:N, Low M.C., Hi Por.	Medium	40%	Adjusted and Maintained
6	Hi C:N, Low M.C., Hi Por.	High	40%	Adjusted and Maintained
7	Med C:N, Hi M.C., Hi Por.	Medium	60%	Adjusted and Maintained
8	Hi C:N, Hi M.C., Hi Por.	High	60%	Adjusted and Maintained
R 1	Med C:N, Hi M.C., Hi Por.	Medium	60%	Adjusted and Maintained
R 2	Med C:N, Hi M.C., Hi Por.	Medium	60%	Adjusted and Maintained
L 1	Low C:N, Hi M.C., Low Por.	Low	60%	Initially adjusted
L 2	Low C:N, Low M.C., Low Por.	Low	40%	Initially adjusted
L 3	Low C:N, Hi M.C., Hi Por.	Low	60%	Adjusted and Maintained
L 4	Low C:N, Low M.C., Hi Por.	Low	40%	Adjusted and Maintained
C 1	Control Pile			

3.1.5 Operational Activities

The pile sections were mixed and built with a front end loader. A windrow turning machine was initially used to mix the materials and aerate the windrows but using the machine resulted in some mixing of the pile materials from adjacent pile sections. The pile section boundaries were restaked after using the windrow turning machine. The varying amounts of straw in the pile sections allowed for the redetermination of the pile section boundaries. It was very difficult to adequately mix the compost materials with a front end loader. This was especially so in the pile sections with straw and grass mixtures. The unchopped straw often remained in small bundles which were required to be broken up and mixed with a pitchfork. Table 3.5 indicates the days and the equipment was used.

Table 3.5 - Days Compost Windrows Turned

Windrow	Days				
1	5*	8	14*	27	47
2	4*	7	13*	26	46

***Windrow turned with Scat machine and front end loader**

The porosity adjusted pile sections (+1 experimental level) 5, 6, 7, 8, R1, R2, L3, L4 were also mixed when additional wood chips were added. Wood chips were added to piles 6 and 7 on day 71, pile 5 on day 70, pile section 8, L3 and L4 on day 77 and pile R1 and R2 on day 78. The dry wood chips ranged in size from approximately 1.25-2.54cm in diameter.

The moisture content of the various pile sections were adjusted by watering the piles with a fire hose or using pumper trucks. A pumper truck was used only twice, on the first day the windrows were built and on September 15, 1992. The method of watering may have effected the ability to adequately maintain the desired moisture contents. It was difficult to adequately control the water volumes and application rates using a fire hose even though the water was metered. From initial recorded volumes, the

high moisture piles only accepted approximately 4-6m^3 of water per watering. The watering operation consisted of watering each pile section on one side of a windrow and then carrying out the same procedures on the other side of the windrow. The application rates varied and the compost piles would not accept the amount of water calculated to increase the moisture content to the desired levels. At a certain point during the watering operations of a particular pile section, water would run out from the bottom of the pile section indicating the addition of more water at that moment was useless. As a result of experimentation, it was found that additional water could be applied to the pile sections after a reasonable period but again water would eventually run out from the bottom of the pile. The watering duration and application rate effect the amount of moisture that could be added to the pile sections.

Environmental factors such as the amount of precipitation and ambient air temperatures may have influenced the moisture content. High ambient air temperatures will increase evaporation losses especially from the outer layers of the compost piles. Although it is difficult to quantify the impact of the precipitation, two observations were noted. Firstly, after a significant rain only the top 25 to 50mm (approximately) of the outer layer seemed to be wet. Secondly, when the snow cover melted in late March and early April, the top 100 to 150mm of the outer layer also seemed quite moist compared to the inner layers. Table 3.6 shows the days the pile sections were watered.

Table 3.6 -Pile Sections -Moisture Additions

Windrow	Days					
1	1*	13	32	47*	51	73
2	1*	12	32	46*	50	72

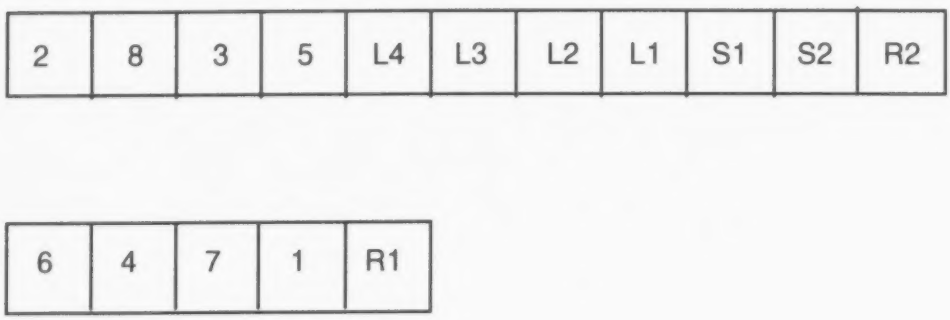
*** Pile section watered with pumper truck**

The final operational activity, except for sampling and measurements, was the rebuilding and covering of the various pile sections to prepare them for the colder temperatures expected in

the fall and winter periods. The rebuilding process involved the installation of passive aeration piping, increasing the height and width of the pile sections, and covering the piles with burlap cloth and a compost cover. Starting with windrow 2, pile section 2 the compost material was spread out and levelled to a height of approximately 15.2 to 20.3cm. Three or four 50.8mm diameter perforated pipes were placed approximately 46cm apart perpendicular to the longnitudinal axis of the windrow. The pipes were placed on a thin bed of straw (15.2cm) and were lightly covered with additional straw (approximately 51mm) to allow for air movement. The compostable materials were placed on top of the pipes and were built into a windrow. The windrow was covered with burlap and then approximately 61cm of mature compost for insulation purposes. The burlap material was used to separate the compost cover from the experimental compost materials. Each pile section was developed using the same procedure.

When the compost cover was placed over the burlap covered piles the ends of the 50.8mm diameter pipes were buried. Each pipe end was uncovered by hand digging and a 61cm long 76.2mm diameter pipe is added to both ends of each pipe to allow for the movement of air into the pipes. Pile sections 2, 8, 5, 3, L3 and L4 (day 84) and L1 and L2 (day 85) were rebuilt on October 23, 1992. Pile sections 6, 4, 7, 1, R1, R2, (day 88) were rebuilt on October 26, 1992. Figure 3.2 shows the reconfigured layout of the pile sections.

Figure 3.2 Reconfigured Compost Pile Sections Layout



Pile No.	Pile Designations
1	Med C:N, Low M.C., Low Por.
2	Hi C:N, Low M.C., Low Por.
3	Med C:N, Hi M.C., Low Por.
4	Hi C:N, Hi M.C., Low Por.
5	Med C:N, Low M.C., Hi Por.
6	Hi C:N, Low M.C., Hi Por.
7	Med C:N, Hi M.C., Hi Por.
8	Hi C:N, Hi M.C., Hi Por.
R 1	Med C:N, Hi M.C., Hi Por.
R 2	Med C:N, Hi M.C., Hi Por.
L 1	Low C:N, Hi M.C., Low Por.
L 2	Low C:N, Low M.C., Low Por.
L 3	Low C:N, Hi M.C., Hi Por.
L 4	Low C:N, Low M.C., Hi Por.

S1 and S2 - Non Factorial Piles

3.2 Method and Materials

3.2.1 Windrow Feedstock Materials

Yard waste consisting mainly of grass and some other plant matter was the primary feedstock material. The addition of barley and wheat straw was used to adjust the C:N ratio and wood chips were added to increase the porosity of the windrow piles. Three front end loader buckets of barley straw and 2.75 buckets of wheat straw was added to the high C:N ratio piles. Two front end loader buckets of barley straw was added to the medium C:N ratio piles. The wood chips were assumed not to contribute to the C:N ratio due to its resistance to degradation.

3.2.2 Field Data Collection

3.2.2.1 Temperature and Oxygen Measurements

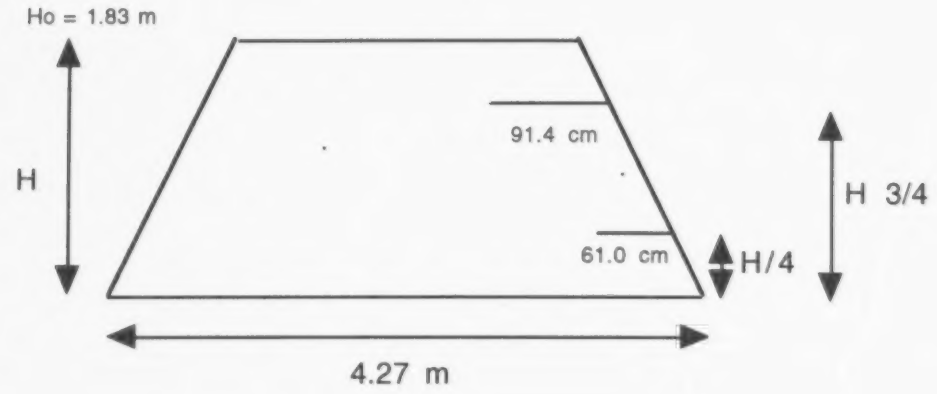
Windrow temperature and % oxygen readings were taken at selected locations in each windrow section.as shown in the Figure 3.3. Percent oxygen readings were initially taken 2-3 times a week from August 14 to September 17, 1992 and weekly for of the remainder of the composting period using a oxygen monitor (Model OX-231, Industrial Scientific Corp.). The meter and aspirator bulb pump and tubing were attached by latex tubing to a 6.35mm (1/4 inch) diameter, 152.4cm long stainless steel probe. To take a reading, a flat-head roofing nail was placed into the lead end of the probe to prevent clogging. The probe was then inserted horizontally into the windrow at the selected location and pulled back approximately 25 - 51mm to remove the nail. The compost pore gas was then sampled by hand pumping, the aspirator bulb, drawing a gas sample through the probe and tubing and past the oxygen meter sensor. After approximately 10-20 seconds of pumping, the oxygen reading stabilized and was recorded. The oxygen meter was calibrated using an ambient air concentration of 20.8%. Calibrating the meter against standard gas samples would be more accurate.

Windrow temperature readings were taken by inserting 91.4cm (3ft) and 121.9cm (4ft) long thermometers (Reotemp Instrument Corp., San Diego, California) into the windrows at the selected locations. The temperature readings were taken approximately 18

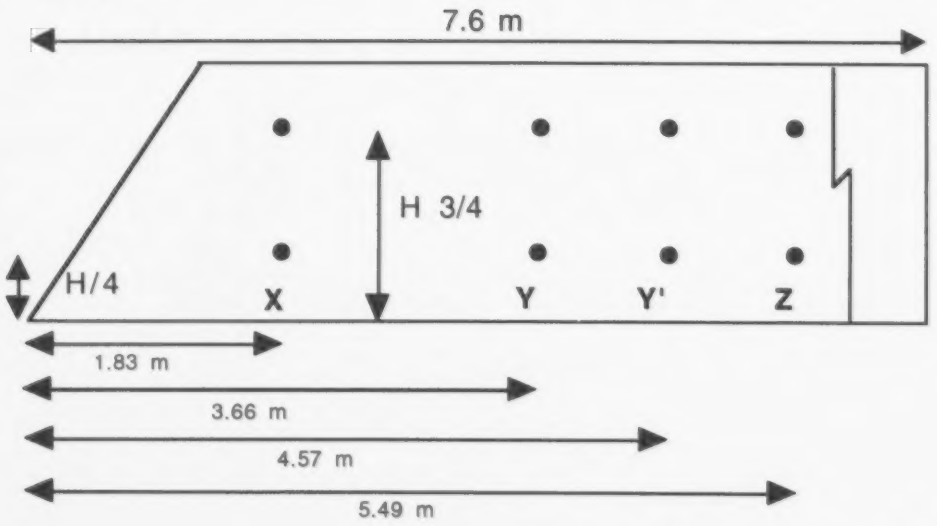
times in August and then the frequency was reduced to about twice per week in September, October and November, and weekly in the months of December, January and February. Twice monthly temperature measurements were taken in March and April. The thermometers were calibrated by placing the end of the thermometers into samples of both boiling and freezing water.

Figure 3.3 Windrow X - Section and Measurement Locations

End View



Side View



3.2.2.2 Bulk Density Measurements

The wet bulk densities (ρ_b) for each windrow section were determined by filling a 90.92 liter plastic refuse container with compost and weighing the sample. The refuse container was filled by placing compost into the container using a pitchfork. When the container was full, the compost was tamped with the pitchfork so it was level with the rim of the container prior to weighing. The weighing apparatus consisted of two bathroom scales and a 1.22m long 50.8mm x 254mm wooden board. The bathroom scales were situated equidistant from a center line and the wooden board is placed on top of the scales. The empty or full container was placed in the middle of the board and the weight showing on each container is recorded. The wet density of the compost was determined by adding the weight indicated on both scales (minus container and wooden board weight) and dividing by the capacity of the container. The measurements were taken in lbs and were converted to grams in the calculations. The dry bulk density (ρ_{bd}) was calculated according to the following equation.

$$\rho_{bd} = \rho_b * 100 /(100 + \% MC) \qquad (18)$$

ρ_{bd} = Dry bulk density (Kg/m^3)
ρ_b = Wet bulk density (Kg/m^3)
% MC = % moisture content (wet basis)

3.2.2.3 Sampling Methods and Procedures

Compost samples for the piles sections were generally collected on the same dates, except when multiple samples were collected per pile or when conditions prevented it. Multiple samples were collected for piles 1 to 8 and R1 and R2 on selected dates to establish the variance of volatile solids measurements in samples taken at different locations in the piles. The samples were taken randomly with the compost sampler at locations X, Y, Z and Y' along the length of the pile as indicated in Figure 3.3. Sampling days were listed in Table 3.7 as shown below. The multiple-sample collection days are highlighted in bold.

Table 3.7 - Pile Section Sampling Days

Pile No.	Pile Designations	Days											
1	Med C:N, Low M.C., Low Por.	3	12	17	24	34	45	58	82		112	165	225
2	Hi C:N, Low M.C., Low Por.	2	11	16	23	35	44	57		97	111	164	224
3	Med C:N, Hi M.C., Low Por.	2	11		23	35	44	59	79		111	166	224
4	Hi C:N, Hi M.C., Low Por.	4	12		24	34	45	58	77		112	165	225
5	Med C:N, Low M.C., Hi Por.	2	11		23	35	44	59	76		111	166	224
6	Hi C:N, Low M.C., Hi Por.	4	12		24	34	45	58	77		112	165	225
7	Med C:N, Hi M.C., Hi Por.	3	12		24	34	45	58	77		112	165	225
8	Hi C:N, Hi M.C., Hi Por.	2	11		23	35	44	59	79		111	164	224
R1	Med C:N, Hi M.C., Hi Por.	3	12		24	34	45	58	77		112	165	225
R2	Med C:N, Hi M.C., Hi Por.	3	12		24	34	45	58	77		112	165	225
L1	Low C:N, Hi M.C., Low Por.	3	12	17	28	37	45	60	82		114	167	225
L2	Low C:N, Low M.C., Low Por.	3		17	28	37	45	60	82		114	167	225
L3	Low C:N, Hi M.C., Hi Por.	2	11	16	27	36	44	59	81		113	166	224
L4	Low C:N, Low M.C., Hi Por.	2		16	27	36	44	59	81		113	166	224
C1	Control Pile		8	13		31	41	60	78		108	163	221
C2	Control Pile		8	13		31	41	60	78		108	163	221

The initial samples were collected by digging with a pitch fork into randomly selected locations within each pile section and then the grab samples were blended to form a representative sample. Obtaining a representative sample of the compost was difficult given the large mass of each pile section. The grab sampling method made it difficult to control the relative amounts of pile interior material versus exterior sample. In addition, obtaining a representative sample from the high straw content pile sections was a challenge because some of the straw remained in small bundles. Although the grab samples were hand mixed in the sample bag, the randomly selected grab sample may contain a large proportion of straw. To obtain a more representative sample, a compost core sampler was developed. From September 2, 1992, the samples were taken at randomly selected sites within the piles by using a compost sampler specifically built to take cores of the windrow sections. The core barrel of the compost sampler was 609.6mm in length and 101.6mm in diameter. A hole saw blade was welded to the end of the barrel to provide the cutting action required to cut the compost cores. To obtain a compost sample for the entire height of the pile two core samples were taken at each location (same entry point). The cores were usually compressed into the lower part of the core barrel and had to be pushed out using a piston located inside the core barrel. The samples were hand mixed and placed in 27 x 28cm plastic zip-lock bags and stored in a refrigerated room at 4^{0}C until analyzed.

3.2.3 Laboratory Analyses - Solid Samples

3.2.3.1 Percent Moisture Content

Total dry solids and moisture content of the compost samples were determined by oven drying pre-weighed samples at 103^{0}C for 24 hrs. As there appeared to be no standard methods to determine compost parameters, the Standard Method 2540 G (APHA-AWWA-WPCF 1989) for determining the total dry solids of water and wastewater was generally used. The drying time of 24 hrs was selected based on repeated cycles of drying, cooling, dessicating and weighing the compost sample until a constant weight was obtained. The samples were weighed on a top loading balance (Mettler PJ400, Greifensee, Switzerland). Percent moisture content was calculated according to the following equation:

$$\% \text{ M.C.} = \frac{(Ww - Wd) * 100}{Ww} \qquad (19)$$

Ww = Wet weight (g)

Wd = Dry weight (g)

3.2.3.2 Volatile solids

Volatile solids analyses were determined by igniting oven dried samples at 550^{0}C in a muffle furnace for 4 hours. Standard Method 2540 G (APHA-AWWA-WPCF 1989) for determining the % volatile solids of water and wastewater solid and semisolid samples was generally used. The ignition time of 4 hrs was selected based on some preliminary tests. Repeated cycles of igniting, cooling, dessicating and weighing the compost residue were carried out until a constant weight was obtained. The samples were weighed on an analytical balance, capable of weighing to 0.1mg (Mettler AE 166, Greifensee, Switzerland). The dried compost samples were not ignited over a gas burner prior to placement in the muffle furnace. Covers were loosely placed on the crucibles for the first 10 minutes to reduce material losses caused by the initial flashing of the dried materials. After 10 minutes, the crucibles covers were placed in a slightly ajar position for the remainder of the process. Wood chips were removed from the sample prior to

weighing and ignition. Three laboratory samples were analyzed for each bulk compost sample.

The compost materials used for volatile solids determination were not ground prior to placement in the muffle furnace except for the last two samples collected for each pile. Ground samples would be more consistent in content than the laboratory grab samples used.

Percent volatile solids (%VS) was calculated according to the following equation:

$$\% VS = \frac{(A-C) * 100}{A-B} \qquad (20)$$

A = weight of dried residue + crucible before ignition (g)
B = weight of crucible (g)
C = weight of residue + crucible after ignition (g)

3.2.3.3 Percent Carbon

The percent carbon of the compost material can be roughly estimated by the following formula developed by New Zealand researchers in the 1950's. (Golueke 1972)

$$\% C = \frac{(100 - \% Ash)}{1.8} \qquad (21)$$

The % ash content was determined from the % volatile solids test data. The ash content was the residue remaining after igniting the dried compost sample in the muffle furnace for 4 hrs. The 1.8 factor is similar to the 1.724 " Van Bemmelen multiplier factor" used to estimate the total organic matter of a soil from values for the organic carbon content. The Van Bemmelen factor is based on the assumption that soil organic matter contains 58% C. (Methods of Soil Analysis 1965).

3.2.3.4 Total Kjeldahl Nitrogen (TKN)

The compost samples were oven dried at 103^{0}C, and ground and sieved through a 2mm mesh sieve in preparation for nitrogen analysis and the development of water extracts. The total kjeldahl nitrogen content of the compost samples were determined following procedures used for analyzing the protein content of animal feed

samples (Animal Science Department, University of Alberta). Due to time and resource constraints generally one laboratory sample per bulk sample was analyzed for total kjeldahl nitrogen content. Multiple laboratory samples were analyzed for randomly selected samples to provide an indication of the variance.

3.2.3.5 Particle Density and Porosity Determination

The particle density of the compost samples were determined using two methods. The first method involved determining the specific gravity of compost particles and calculating the particle density using the equation listed below:

$$\rho_c = G_c \cdot \rho_w \qquad (22)$$

ρ_c = compost particle density (Kg/m^3)
G_c = specific gravity of compost particles
ρ_w = density of water (Kg/m^3)

The specific gravity of the compost particles for the tested samples were determined by adapting a procedure for the determination of specific gravity of soil particles (Whitlow 1990). The method involved placing a known weight of oven dried compost sample (50 to 60g including wood chips) into a 500ml graduated cylinder containing 400ml of distilled water. The contents of the graduated cylinder were stirred with a glass rod to assist in the removal of the trapped air. After carefully topping-up to the 500ml mark with distilled water the weight of the graduated cylinder containing the compost sample was taken. The absorption of water by the compost material while in the graduated cylinder is a possible source of error. To minimize the error, the compost sample was in the graduated cylinder containing water for approximately 5-10 minutes. The specific gravity of the compost particles was calculated using the following equation:

$$G_c = \frac{M_c}{M_4 - M_3 + M_c} \qquad (23)$$

M_c = mass of compost (g)
M_1 = mass of empty 500 ml graduated cylinder (g)
M_3 = mass of graduated cylinder + compost + water (g)
M_4 = mass of graduated cylinder + water only (g)

The second method of determining the compost particle density was based on a water displacement principle. The volume of water displaced when the known mass of dried compost sample was added to the graduated cylinder (containing water) as described in method one was noted. The particle density was then calculated by dividing the compost weight by the amount of water displaced. The particle density values for both methods were similar however the first method is considered more reliable because of the level of accuracy in measuring the volume of water displaced in the second method. Triplicate measurements were carried out for each bulk compost sample analyzed.

The porosity of the compost was determined according to the equation listed below:

$$\text{Porosity} = 1 - (p_b / p_c) \qquad (24)$$

p_c = compost particle density (Kg/m^3)
p_{bd} = Dry bulk density (Kg/m^3)

3.2.3.6 Oxygen Uptake Rates (OUR)

OUR measurements of the compost samples were taken using a oxygen monitor (model OX-231, Industrial Scientific Corp.) and a 500 ml Erlenmeyer flask as the reaction vessel. Approximately 100 g of compost was placed in the reaction flask, the rubber stopper was installed and a hand bulb pump was used to pump air from the reaction flask past the oxygen meter sensor and back into the reaction vessel. The percent oxygen readings were initially taken at 5 minute intervals and then at 20 minute time intervals. The outlet and inlet tubes were pinched off with clamps after each reading. The percent oxygen readings decreased with time: however, oxygen leaked into the system resulting in higher oxygen readings. After

many attempts to identify and seal the leaks and run OUR tests without success, the OUR parameter was dropped from the experimental plan.

3.2.4 Laboratory Analyses - Water Extracts

Water compost extracts were obtained by mechanically shaking oven dried compost samples with distilled water for 2 hours (solid liquid ratio = 1/10). The extracts were centrifuged at 5,000g for 20 minutes, and filtered through a Watsman No. 1 filter paper (11 μm). The water extracts were developed using the method used by Garcia *et al.* (1991b).

The water extracts were analyzed immediately for NH_3 and organic nitrogen and were stored in teflon sealed glass bottles in a refrigerated room at 4^0C until they were analyzed for carbon content.

3.2.4.1 Total Organic Carbon (TOC) Content

The total carbon (TC) and total inorganic carbon (TIC) content of the compost water extracts were determined by using a Dohrman DC-80 Organic Carbon Analyzer. The water extracts were diluted 10 fold prior to injection Using a volumetric pipet, 1 ml of compost water extract was transferred to a 10ml volumetric flask and topped up with. distilled water. The total organic carbon (TOC) content was calculated by subtracting the TIC value from TC value for each water extract sample. At least three syringe injections per extract were performed. Multiple extracts were developed and analyzed for selected samples to provide an indication of variance.

The compost water extracts were prepared from ground, oven-dried samples versus air dried samples. This sample preparation method may have introduced some possible errors in the TOC results. Drying the samples at the higher temperature would result in potential volatile organic and ammonia losses, and hence, affect the water extract results. Jimenez and Garcia (1992b) found there was only about a 1.2 to 1.8% more water soluble carbon in air dried and ground samples than in fresh samples. The volatile organic and

ammonia losses may not be significant at the 103°C temperature. Tests would be required to assess the potential losses.

An additional source of error was the time required to filter the compost water extracts. To obtain enough water extract for analyses, the earlier grass-like samples required approximately 30 additional minutes of filtration time. The longer filtration times introduced possible losses in TOC and ammonia.

The errors introduced in obtaining the initial compost samples are perhaps larger in magnitude than the errors due to sample drying and water extract preparation.

3.2.4.2 Organic and Ammonia Nitrogen

The organic and ammonia nitrogen contents of the water extracts were determined by the Kjeldahl method described in Standard Methods for the Examination of Water and Wastewater 1989, 17th edition. Generally, duplicate aliquots of the water extracts were analyzed for NH_3 and organic nitrogen content.

4.0 RESULTS AND ANALYSIS

This section of the thesis reviews the results of the factorial experiments, discusses the decomposition kinetics of the various compost piles and the results of the ARIMA (Autoregressive integrated moving average) analyses of pile temperature data.

4.1 Factorial Experiments

The purpose of the field factorial experiments were to systematically evaluate the influence of key operational parameters on the decompostion rate of yard waste in a windrow type operation. The following sections describe the changes in operational and response variables and the results of the factorial experiments.

4.1.1 Trends in Operational Variables

4.1.1.1 C:N ratio

The C:N ratio of the various piles generally followed a decreasing trend throughout the first 112 days of the process, the active composting phase, and then remained fairly constant or varied slightly during the remaining 113 days, the maturation phase, of the process. Figures 4.1 to 4.8 show the C:N ratio versus composting days for the low, medium and high C:N ratio pile sections, as well as control piles C1 and C2 and the replicate piles R1 and R2.

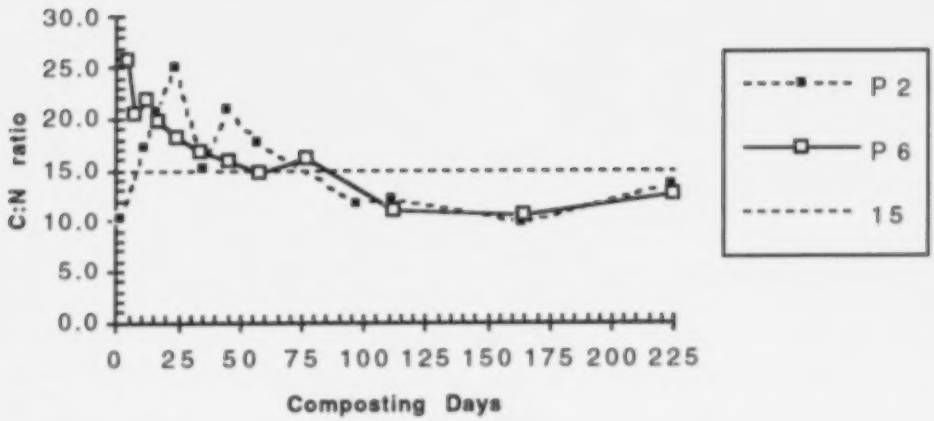


Figure 4.1 C:N ratio vs Composting Days - Piles 2 and 6
Hi C:N, Low M.C.

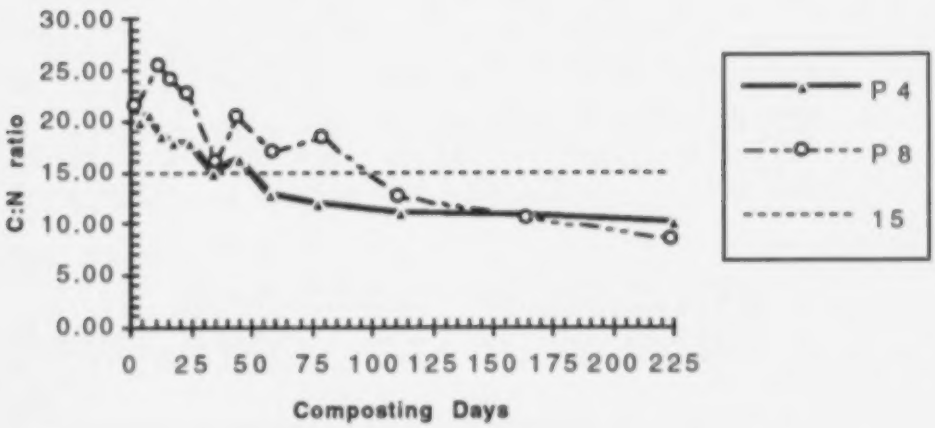


Figure 4.2 C:N ratio vs Composting Days - Piles 4 and 8
Hi C:N, Hi M.C.

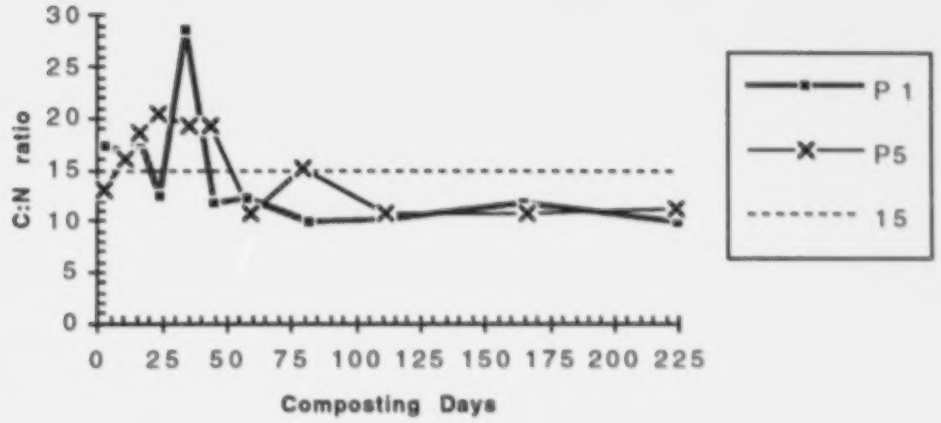


Figure 4.3 C:N ratio vs Composting Days - Piles 1 and 5
Med C:N, Low M.C.

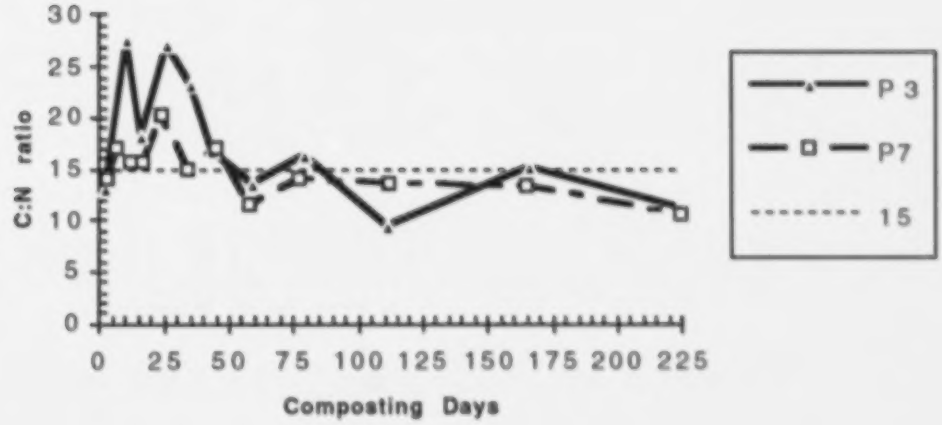


Figure 4.4 C:N ratio vs Composting Days - Piles 3 and 7
Med C:N, Hi M.C.

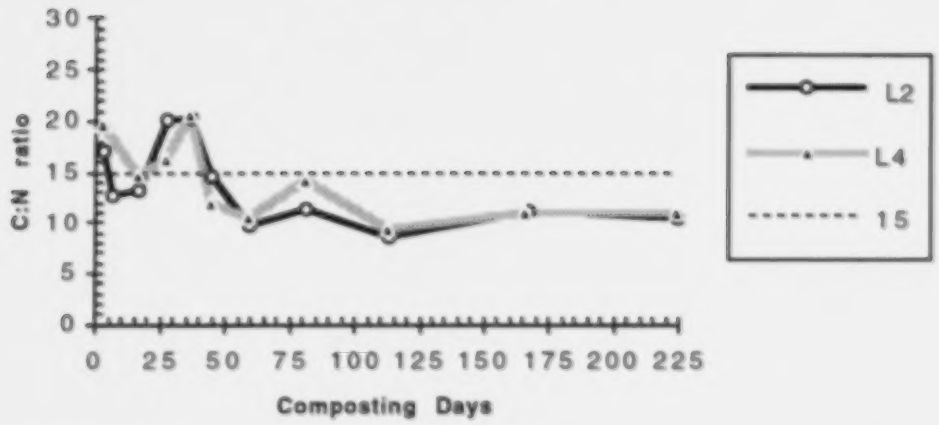


Figure 4.5 C:N ratio vs Composting Days - Piles L2 and L4

Low C:N, Low M.C.

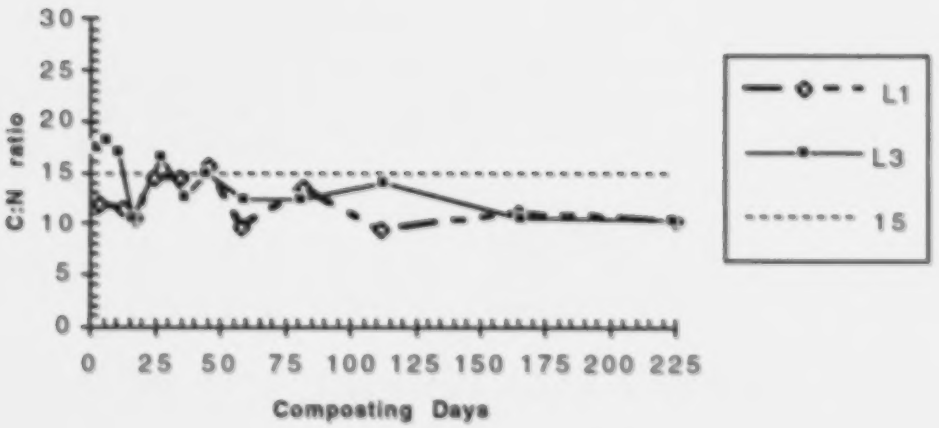


Figure 4.6 C:N ratio vs Composting Days - Piles L1 and L3

Low C:N, Hi M.C.

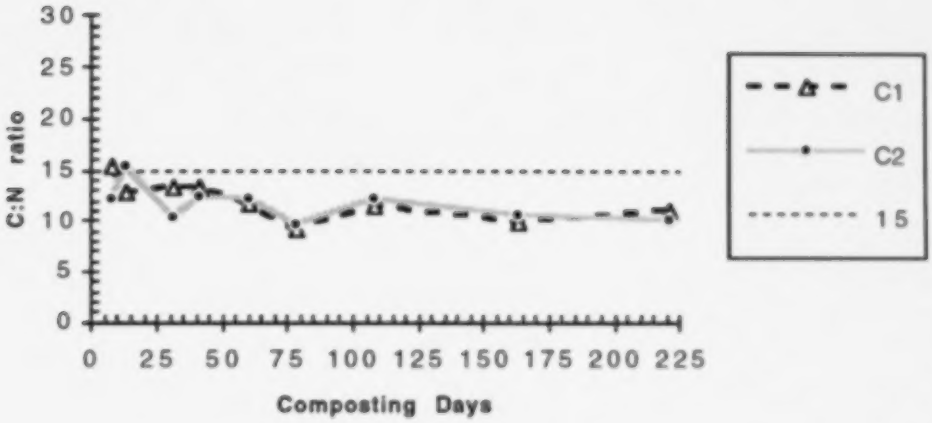


Figure 4.7 C:N ratio vs Composting Days - Piles C1 and C2
Control Piles

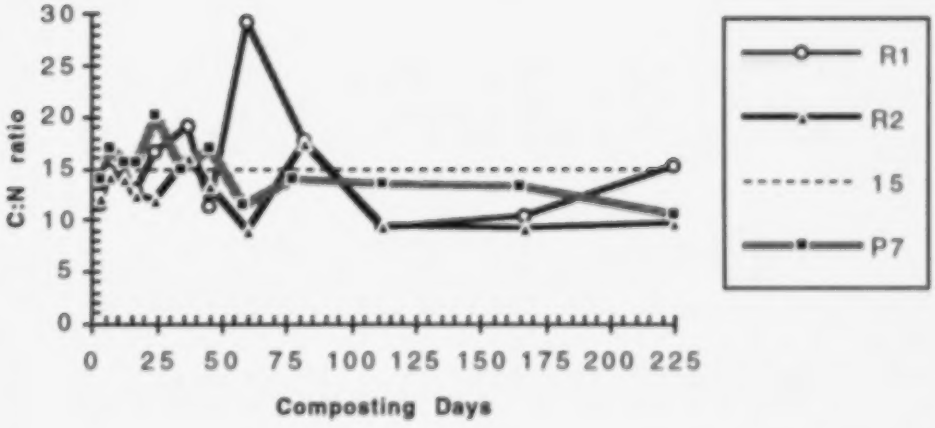


Figure 4.8 C:N ratio vs Composting Days - Piles 7, R1 and R2
Med C:N, Hi M.C.
Replicates

The C:N ratio values of the different piles generally fluctuated more during the first 35 to 45 days of the process and usually increased from the initial values during this period. Possible reasons for the fluctuations in the C:N ratio values are inadequate mixing, sampling errors, ammonia losses and the amount of straw added to the piles. Figure 4.8 clearly shows the variability in the C:N ratio data for piles with the same experimental design. Table 4.1 lists the initial and final C:N ratio values for the various piles.

Table 4.1 - Initial and Final Pile C:N Values

Pile No.	Pile Designation	Initial C:N ratio	Final C:N ratio
1	Med C:N, Low M.C., Low Por.	17.12	9.72
2	Hi C:N, Low M.C., Low Por.	10.19	13.49
3	Med C:N, Hi M.C., Low Por.	13.12	11.19
4	Hi C:N, Hi M.C., Low Por.	20.08	9.99
5	Med C:N, Low M.C., Hi Por.	13.13	11.11
6	Hi C:N, Low M.C., Hi Por.	25.80	12.57
7	Med C:N, Hi M.C., Hi Por.	13.92	10.52
8	Hi C:N, Hi M.C., Hi Por.	21.60	8.46
R1	Med C:N, Hi M.C., Hi Por.	11.45	15.15
R2	Med C:N, Hi M.C., Hi Por.	12.20	9.68
L1	Low C:N, Hi M.C., Low Por.	11.93	10.36
L2	Low C:N, Low M.C., Low Por.	17.03	10.29
L3	Low C:N, Hi M.C., Hi Por.	17.33	10.30
L4	Low C:N, Low M.C., Hi Por.	19.83	10.87
C1	Control Pile	15.27	11.07
C2	Control Pile	12.09	10.12

The initial C:N ratio values for piles sections L1 to L4 varied from 12:1 to 19:1. The final C:N ratio values for piles L1 to L4 were all approximately 10:1. The medium C:N ratio piles 3, 5 and 7 had initial values of about 13:1 and final C:N ratio values of approximately 11:1. Pile 1, the other medium C:N ratio pile section, had a starting value of about 17:1 and a final value of 13.5:1. The high C:N ratio piles 2, 4, 6 and 8 had initial C:N values from about 10:1 to 26:1 and final values varying from 8.5:1 to 13.5:1. The high

C:N ratio piles generally had higher C:N ratio values than the medium and low C:N ratio piles. The medium to low C:N ratio piles had similar values mainly because the amount of barley straw initially mixed with the respective pile sections did not increase the C:N ratio as much as expected. The C:N ratio of the barley straw was determined to be 55.7:1 by Norwest Labs, compared to literature values between 129 to 150:1 for wheat straw. At the time of the composting experiment, only barley straw was available. To increase the C:N ratio of piles 2 and 8 (on day 17) and piles 4 and 6 (on day 18) two front end loader buckets of wheat straw were added to each of these pile sections on August 17, 1992. On August 26, 1992 (days 26 and 27 respectively), an additional 3/4 of a bucket of wheat straw was mixed into each of the high C:N ratio piles. One bucket of barley straw was also added to piles 1 and 7 on composting day 18 and piles 3 and 7 on composting day 17 to increase the C:N ratio of the those pile sections. The initial C:N ratios of the City of Edmonton control piles C1 and C2 were 15.3 and 12.1, while the final values were 11.1 and 10.1 respectively.

4.1.1.2 Moisture Content

The factorial experiment included testing the affect of two different moisture content levels on the decomposition of the yard waste. The experimental design called for certain pile sections to be maintained at a moisture content of 60% and others at 40%. It was not possible to maintain the moisture content of the pile sections at the desired levels. As expected, the moisture content of the piles sections generally decreased dramatically during the first 2 to 3 weeks of the process due to evaporative losses as a result of the high temperatures. Water was added to the piles on five occasions to increase the moisture content during the first 73 days of the process. The moisture content generally followed a gradual decreasing trend for the remainder of the composting period. As the compost matured and the temperature of the piles cooled, evaporative losses decreased. The moisture content of the various piles are displayed in Figures 4.9 to 4.16. The vertical dashed lines

in Figures 4.9 to 4.16 represent when the pile sections were watered.

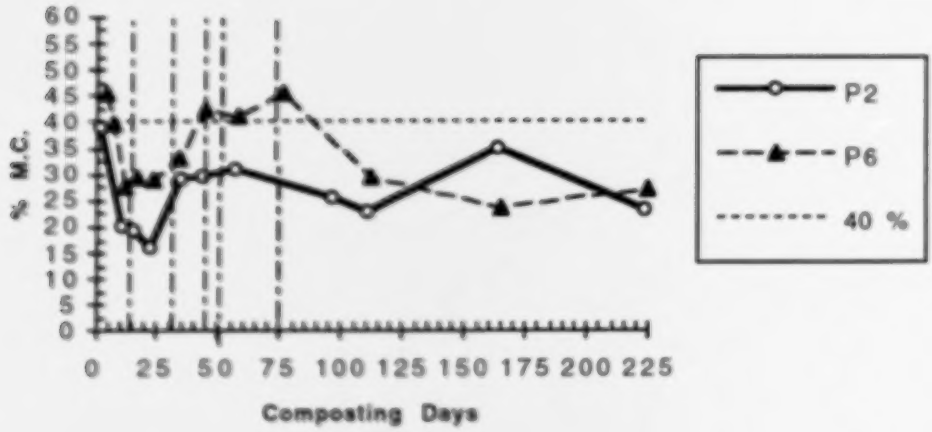


Figure 4.9 M.C. vs Composting Days - Piles 2 and 6
Hi C:N, Low M.C.

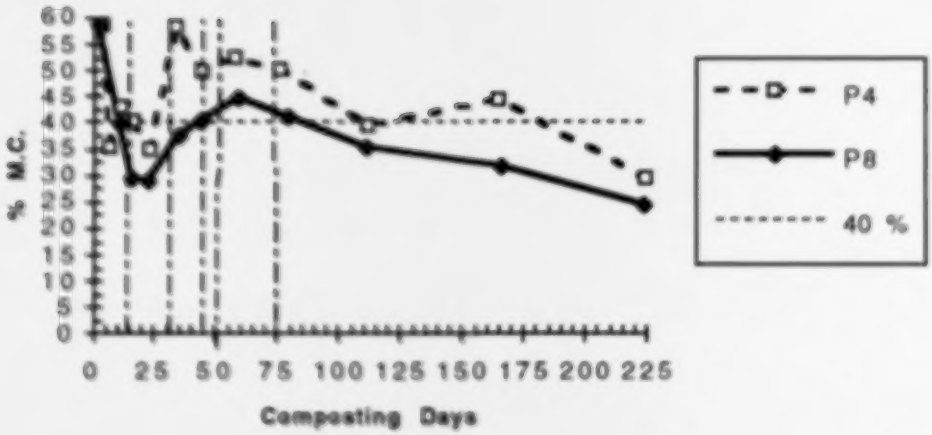


Figure 4.10 M.C. vs Composting Days - Piles 4 and 8
Hi C:N, Hi M.C.

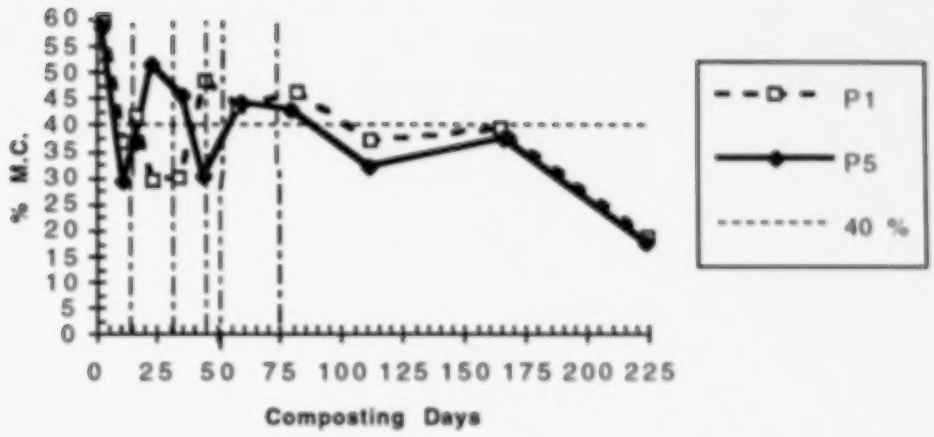


Figure 4.11 M.C. vs Composting Days - Piles 1 and 5

Med C:N, Low M.C.

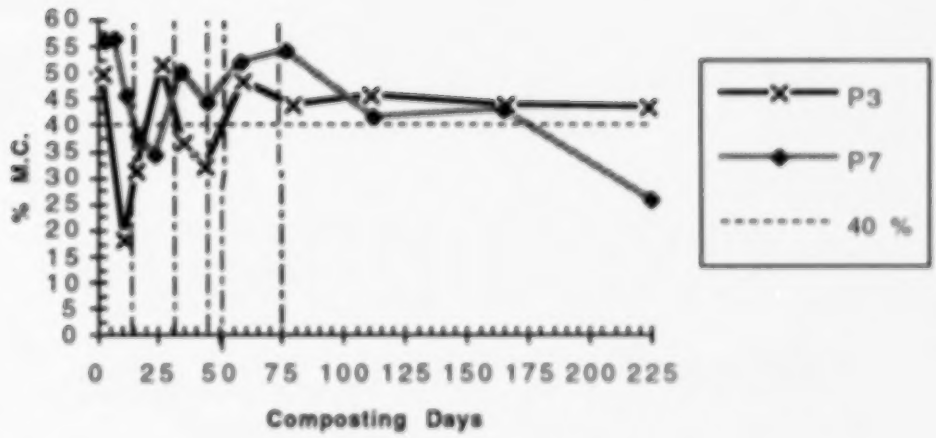


Figure 4.12 M.C. vs Composting Days - Piles 3 and 7

Med C:N, Hi M.C.

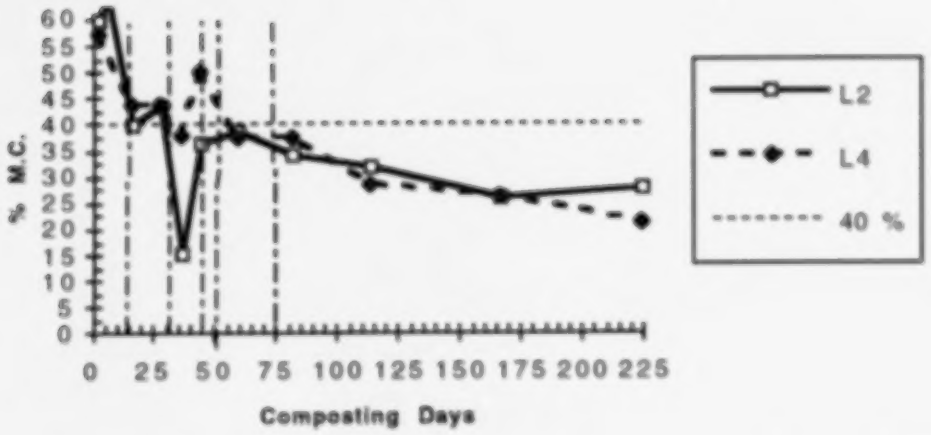


Figure 4.13 M.C. vs Composting Days - Piles L2 and L4
Low C:N, Low M.C.

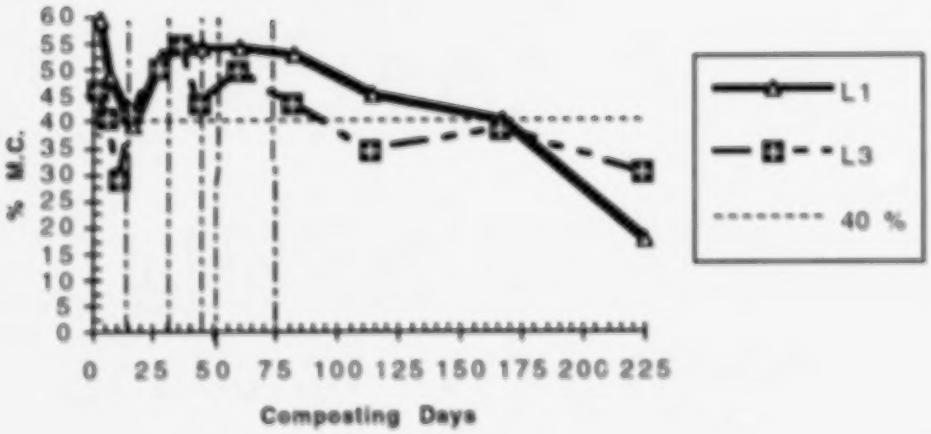


Figure 4.14 M.C. vs Composting Days - Piles L2 and L4
Low C:N, Hi M.C.

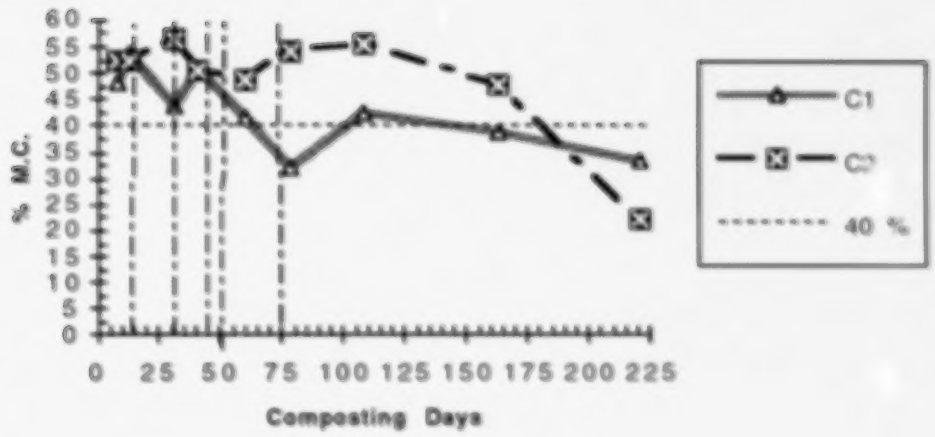


Figure 4.15 M.C. vs Composting Days - Piles C1 and C2 Control Piles

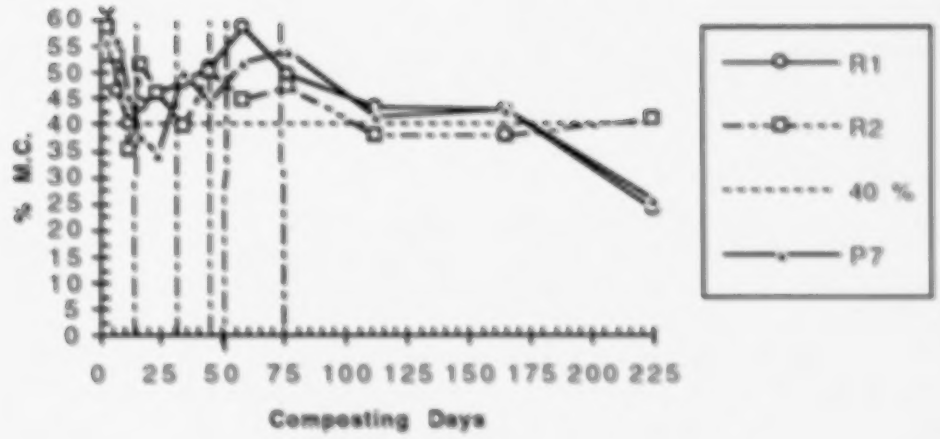


Figure 4.16 M.C. vs Composting Days - Piles R1 and R2 and 7 Med C:N, Hi M.C.- Replicate Piles

The directional changes in moisture content of the piles were consistent with changes described in the literature. Table 4.2 lists the weighted average % moisture contents for the various piles. The weighted average for each pile was calculated by the equation shown

$$\text{Avg \% M.C.} = \frac{\text{Days1*MC1+ Days2*MC2 + ... + Daysn*MCn}}{\text{Days1 + Days2 + ... + Daysn}} \quad (26)$$

MCn = % M.C measurements at different intervals of the composting process.

Daysn = number of composting days between each % M.C. measurement.

Table 4.2 - Weighted Average % Moisture Content of the Compost Piles

Pile No.	Pile Designation	Planned Level	Weighted Avg Full Period	Weighted Avg Active Phase
1	Med C:N, Low M.C., Low Por.	40%	34.4%	40.5%
2	Hi C:N, Low M.C., Low Por.	40%	27.0%	25.2%
3	Med C:N, Hi M.C., Low Por.	60%	42.3%	41.1%
4	Hi C:N, Hi M.C., Low Por.	60%	41.0%	45.7%
5	Med C:N, Low M.C., Hi Por.	40%	32.8%	38.4%
6	Hi C:N, Low M.C., Hi Por.	40%	30.7%	35.9%
7	Med C:N, Hi M.C., Hi Por.	60%	40.1%	46.5%
8	Hi C:N, Hi M.C., Hi Por.	60%	33.1%	38.3%
R1	Med C:N, Hi M.C., Hi Por.	60%	40.6%	48.4%
R2	Med C:N, Hi M.C., Hi Por.	60%	41.7%	43.8%
L1	Low C:N, Hi M.C., Low Por.	60%	39.2%	49.9%
L2	Low C:N, Low M.C., Low Por.	40%	31.3%	35.7%
L3	Low C:N, Hi M.C., Hi Por.	60%	30.6%	42.5%
L4	Low C:N, Low M.C., Hi Por.	40%	30.7%	37.5%
C1	Control Pile	None	39.2%	42.6%
C2	Control Pile	None	43.8%	53.5%
		Avg High M.C. Pile	**38.6%**	**44.5%**
		Avg Low M.C. Pile	**31.2%**	**35.5%**

Active Phase - up to and including samples taken on November 19-21, 1992.

Although is was not possible to maintain the planned experimental moisture content levels, the moisture content for the 60% moisture content piles were generally higher than the 40% moisture piles. The overall weighted average moisture content for the 60% piles was 38.6% with a standard deviation of 3.86 for the full composting period compared to 31.2% with a standard deviation of 5.36 for the 40% moisture content piles. For the period up to and including the November 19-21, 1992 samples, referred to as the active stage, the overall weighted average moisture levels for both the high and low moisture piles were higher than the values calculated for the full composting period. The high moisture level piles had an overall average weighted moisture content of 44.5% for the active period with a standard deviation of 4.31. The overall average weighted moisture level for the low moisture experimental piles during the same period was 35.5% with a standard deviation of 2.49. These values reflect the fact the compost moisture contents of the various piles were higher during the active stages of the composting process, which is desired from an operational viewpoint. The overall weighted average moisture contents for the high and low M.C. piles were found to be significantly different using the Student t test at the 95% confidence level. The calculated t values were 2.86 and 4.95 respectively for the full and active composting period tests compared to t value from the table of 2.18.

In comparison, the overall weighted average moisture content for the control piles C1 and C2 was 2.9% higher for the full composting period and 3.6% higher for the active period than the values calculated for the experimental 60% moisture content pile sections. Piles 7, R1 and R2 having the same experimental treatment design, had an overall weighted average moisture content of 40.8% with a standard deviation of 0.82 for the full composting period. The difficulty experienced trying to maintain the experimental moisture levels may be due to the method of moisture addition, the characteristics of the composting materials, sampling and testing frequency and environmental factors. Environmental factors such as the amount of precipitation and ambient air temperatures may influence the moisture content. High ambient air temperatures will

increase evaporation losses especially from the outer layers of the compost piles. Although it is difficult to quantify the impact of the precipitation, two observations were noted. Firstly, after a significant rain only the top 25 to 50mm (approximately) of the outer layer seemed to be wet. Secondly, when the snow cover melted in late March and early April, the top 100 to 150mm of the outer layer also seemed quite moist compared to the inner layers.

4.1.1.3 Porosity Adjustment

The porosity values for the various piles generally decreased throughout the process with the largest reduction observed in the first 60 days for most piles. This is consistent with the fact the rate of decomposition is higher during the first one or two months of the composting process when the easier degradable components are being broken down. Wood chips were added to pile 5 on composting day 70 and to piles 6 and 7 on composting day 71 to increase the porosity of the compost piles. Additional wood chips were also added to piles R1 and R2 on composting day 78 and to piles 8, L3 and L4 on composting day 77. The wood chip additions did not consistently create a significant increase in porosity values. Figures 4.17 to 4.20 display the porosity values versus composting time for the adjusted and maintained porosity piles.

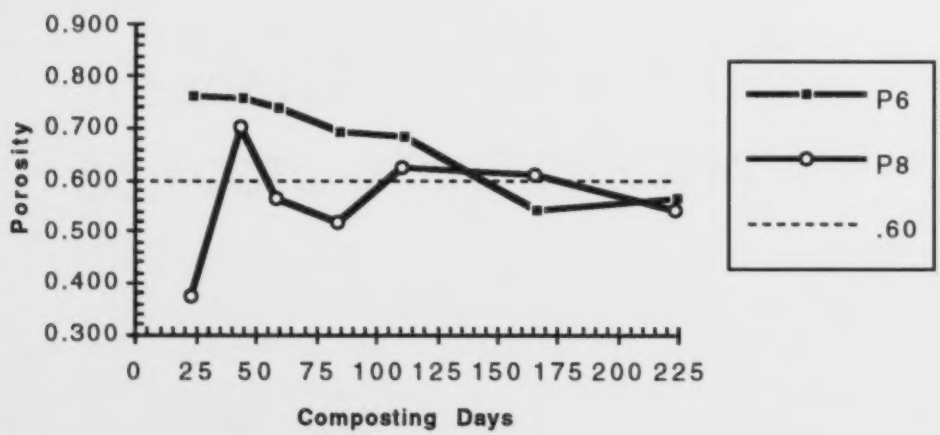


Figure 4.17 **Porosity vs Composting Days - Piles 6 and 8 HI C:N, HI Por.**

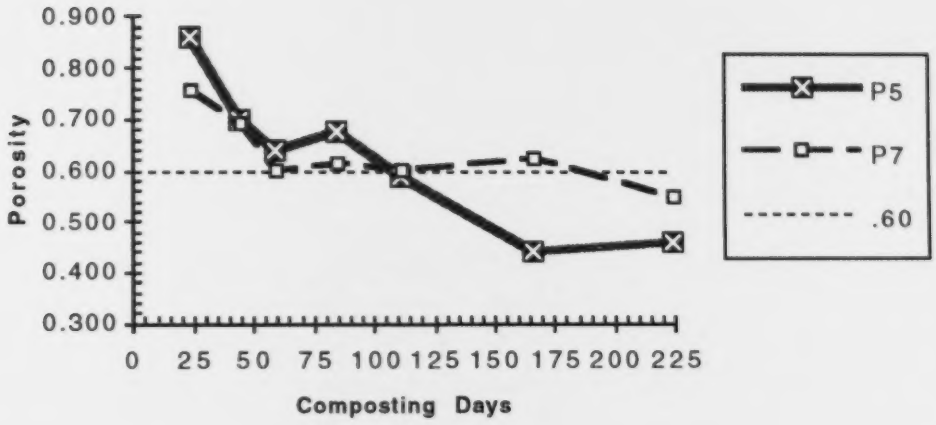


Figure 4.18 **Porosity vs Composting Days - Piles 5 and 7**

Med C:N, Hi Por

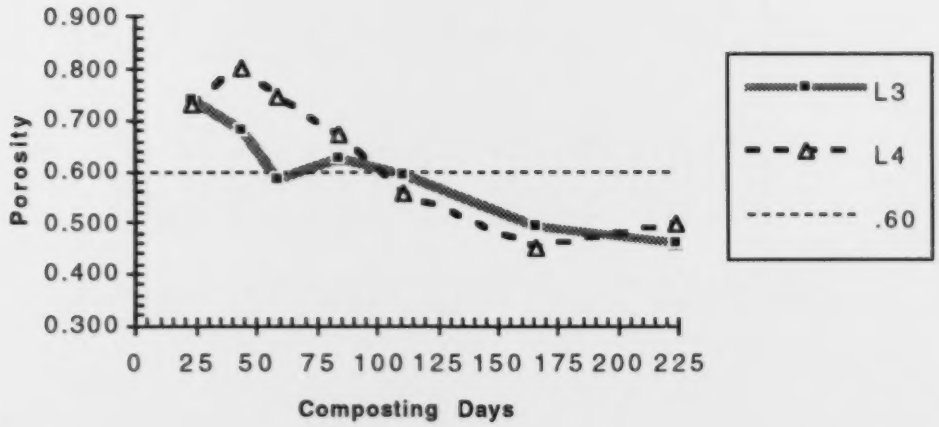


Figure 4.19 **Porosity vs Composting Days - Piles L3 and L4**

Low C:N, Hi Por.

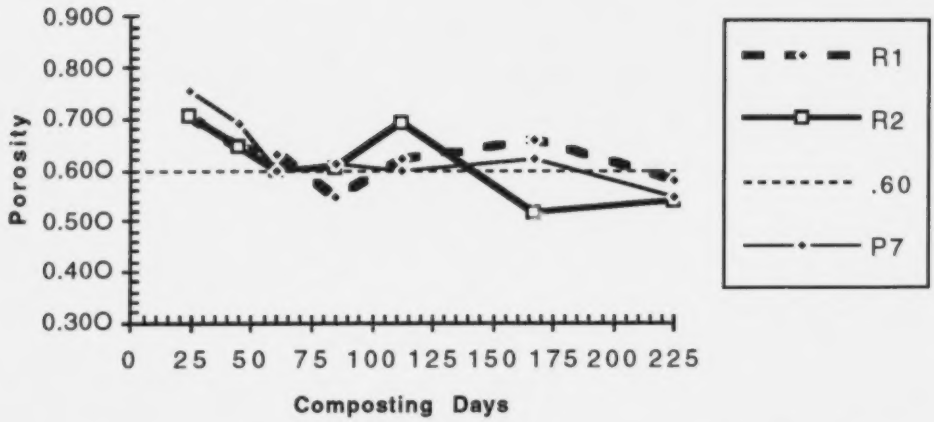


Figure 4.20 **Porosity vs Composting Days - Piles 7, R1 and R2 Med C:N, Hi Por Replicate Piles**

Porosity values for piles 5, 6, 7, L4, R1, R2 and 8 generally decreased or remained fairly level for the first porosity measurements after the addition of more wood chips. The porosity values for Piles 8 and R1 increased for measurements taken in November and January. The porosity values for Pile 1, for example, increased for the October and November samples even though no additional wood chips were mixed into the pile section. Figure 4.21 shows the porosity measurements for Pile 1 vs composting days.

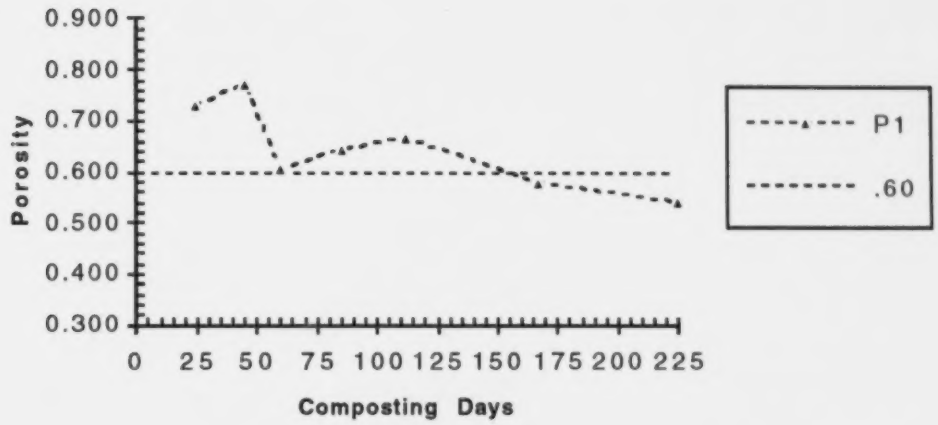


Figure 4.21 **Porosity vs Composting Days - Pile 1**
Med C:N - Porosity Adjusted and Maintained

There is no conclusive evidence indicating the addition of wood chips to certain experimental piles increased the porosity of these piles based on visual observation of the plots. Table 4.3 displays the first and final porosity measurements for the various experimental piles.

Table 4.3 - Pile Porosity Values

Pile No.	Pile Designation	Experimental Plan	Initial Porosity	Final Porosity
1	Med C:N, Low M.C., Low Por.	Initially Adjusted	0.732	0.543
2	Hi C:N, Low M.C., Low Por.	Initially Adjusted	0.685	0.501
3	Med C:N, Hi M.C., Low Por.	Initially Adjusted	0.725	0.579
4	Hi C:N, Hi M.C., Low Por.	Initially Adjusted	0.771	0.534
5	Med C:N, Low M.C., Hi Por.	Adjusted and Maintained	0.861	0.458
6	Hi C:N, Low M.C., Hi Por.	Adjusted and Maintained	0.761	0.561
7	Med C:N, Hi M.C., Hi Por.	Adjusted and Maintained	0.753	0.548
8	Hi C:N, Hi M.C., Hi Por.	Adjusted and Maintained	0.372	0.540
R 1	Med C:N, Hi M.C., Hi Por.	Adjusted and Maintained	0.703	0.578
R 2	Med C:N, Hi M.C., Hi Por.	Adjusted and Maintained	0.702	0.537
L 1	Low C:N, Hi M.C., Low Por.	Initially Adjusted	0.756	0.371
L 2	Low C:N, Low M.C., Low Por.	Initially Adjusted	0.711	0.553
L 3	Low C:N, Hi M.C., Hi Por.	Adjusted and Maintained	0.740	0.460
L 4	Low C:N, Low M.C., Hi Por.	Adjusted and Maintained	0.732	0.497
		Avg	**0.715**	**0.519**
		Stdev	**0.107**	**0.057**

The mean porosity value for the initial tests for the experimental piles was 0.72 with a standard deviation of 0.11. The mean final porosity value for the pile sections was 0.52 with a standard deviation of 0.06. The initial mean porosity value for the initially adjusted (low porosity) piles was 0.73 compared to a value of 0.70 for the porosity adjusted piles. The final mean porosity value for the initially adjusted (low porosity) piles was 0.51 compared to a value of 0.52 for the porosity adjusted (high porosity) piles. There was no statistical difference between the mean porosity values for the high and low porosity piles for both the initial and final porosity values using the t test. The control piles C1 and C2 had an average porosity value of 0.73 for the initial test with a standard deviation of 0.007. The mean final porosity value and standard deviation for the control piles was 0.67 and 0.016. The lower final mean porosity value determined for the experimental piles provides an indication the organic materials in the experimental piles had decomposed further than the yard waste in the control piles.

The porosity values measured for the various piles are similar to values observed by Fleming (1991) in the composting of mixtures of green waste, leaves and wood wastes in Florida. The initial mean porosity for her four experimental windrows was 0.70 compared to 0.72 determined for the experimental piles. The final mean porosity for her windrows was 0.30, which is lower than the final values observed for our composting piles. The difference may be explained by the type of organic materials, testing errors, degree of stabilization, the amount of wood wastes in the windrows. Fleming's two windrows containing approximately 50% wood wastes had final porosity values of 0.336 and 0.356, which supports the comment that the wood chips mixed into our experimental piles may increase the final porosity values.

4.1.2 Trends in Response Variables

The primary response variables used to measure the degree and rate of degradation of the organic materials in these experiments were the percent change in total carbon of solid samples and the percent change in TOC of compost water extracts as well as the more absolute indicator the ratio of Organic C/Organic N ($C:N_w$) of water extracts. The measurements of OUR were not successful, due to problems experienced during testing. No results are available for this parameter. Secondary, but less reliable indicators of maturity used in these studies, are average pile temperatures, percent increases in dry bulk density. Tables 4.4 and 4.5 list the results of the primary response variables as well as % increases in bulk densities over the full and active composting periods.

Table 4.4 - Pile Response Variable Values
Full composting period

		Response Variables		
Pile No.	**Pile Designation**	% Decrease in % C (SS)	% Decrease in TOC (WE)	% Increase in DBD
1	Med C:N, Low M.C., Low Por.	44.7	81.5	49.5
2	Hi C:N, Low M.C., Low Por.	42.7	84.8	55.8
3	Med C:N, Hi M.C., Low Por.	54.5	84.5	46.4
4	Hi C:N, Hi M.C., Low Por.	52.6	61.3	62.6
5	Med C:N, Low M.C., Hi Por.	49.5	80.1	71.3
6	Hi C:N, Low M.C., Hi Por.	56.6	68.2	63.4
7	Med C:N, Hi M.C., Hi Por.	56.1	78.3	47.6
8	Hi C:N, Hi M.C., Hi Por.	73.5	86.0	34.4
R1	Med C:N, Hi M.C., Hi Por.	17.8	80.9	49.9
R2	Med C:N, Hi M.C., Hi Por.	57.1	80.8	48.2
L1	Low C:N, Hi M.C., Low Por.	37.9	83.8	68.3
L2	Low C:N, Low M.C., Low Por.	66.4	82.1	56.9
L3	Low C:N, Hi M.C., Hi Por.	53.3	73.8	60.7
L4	Low C:N, Low M.C., Hi Por.	53.5	68.0	59.9
C1	Control Pile	26.6	Not Tested	34.3
C2	Control Pile	51.6	Not Tested	38.5

WE= Compost water extracts
SS = Compost solid samples

Table 4.5 - Pile Response Variable Values
Active composting period

Pile No.	Pile Designation	Response Variable: % Decrease in % C (SS)	% Decrease in TOC (WE)	% Increase inDBD
1	Med C:N, Low M.C., Low Por.	48.3	80.2	39.6
2	Hi C:N, Low M.C., Low Por.	47.4	81.2	56.7
3	Med C:N, Hi M.C., Low Por.	46.8	81.4	46.7
4	Hi C:N, Hi M.C., Low Por.	50.7	67.6	59.5
5	Med C:N, Low M.C., Hi Por.	45.9	76.3	70.3
6	Hi C:N, Low M.C., Hi Por.	57.0	65.5	53.2
7	Med C:N, Hi M.C., Hi Por.	51.4	81.7	41.0
8	Hi C:N, Hi M.C., Hi Por.	65.9	84.8	30.9
R1	Med C:N, Hi M.C., Hi Por.	37.0	76.5	45.8
R2	Med C:N, Hi M.C., Hi Por.	52.3	65.0	39.9
L1	Low C:N, Hi M.C., Low Por.	45.4	76.2	63.1
L2	Low C:N, Low M.C., Low Por.	68.0	80.1	56.1
L3	Low C:N, Hi M.C., Hi Por.	38.4	64.8	53.0
L4	Low C:N, Low M.C., Hi Por.	48.9	53.1	55.4
C1	Control Pile	19.1	Not Tested	21.1
C2	Control Pile	36.4	Not Tested	-2.4

WE= Compost water extracts

4.1.2.1 Total Carbon

As expected, the percent total carbon (% C) of the various piles decreased throughout the composting period, with most of the decrease observed during the first 50 to 80 days of the process when the more available organic constituents are decomposed. The percent change in the total carbon content of the experimental piles varied from 17.8% for pile R1 to 66.4% for pile L2. The mean value was 51.8% with a standard deviation of 12.9. Control piles C1 and C2 observed a 26.6% and 51.6% decrease in % C. The large difference between the values for the control piles may be due to sampling or testing errors. Figures 4.22 to 4.29 display the percent carbon content over the composting duration for the various pile sections. The piles are organized according to their experimental C:N ratio and moisture levels.

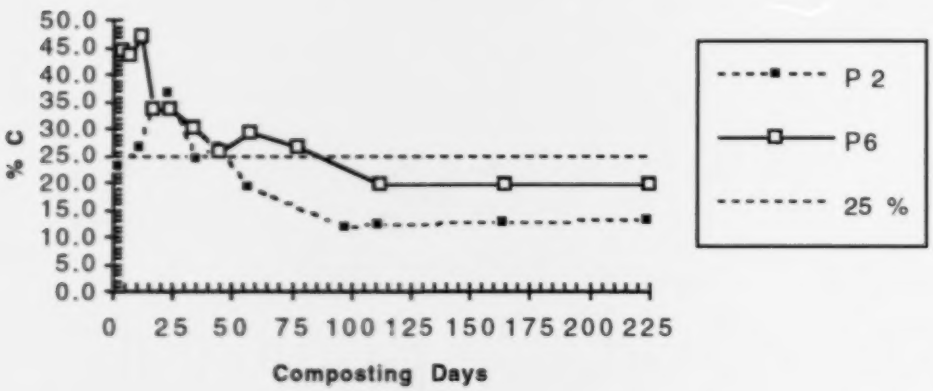


Figure 4.22 **% C vs Composting Days - Piles 2 and 6**

HI C:N, Low M.C.

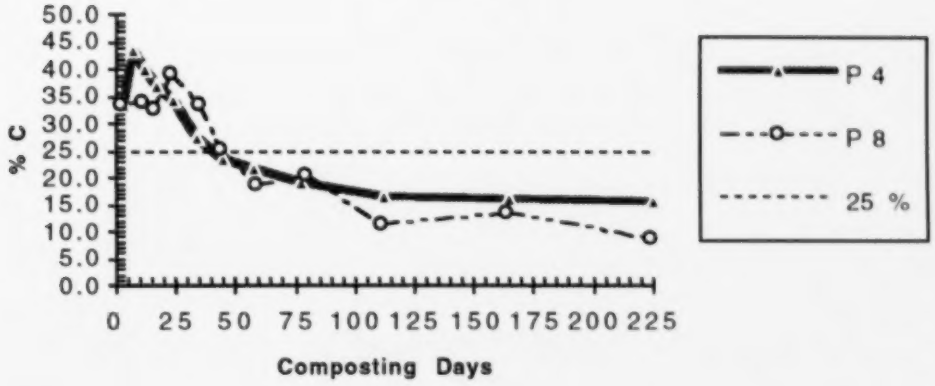


Figure 4.23 **% C vs Composting Days - Piles 4 and 8**

Hi C:N, Hi M.C.

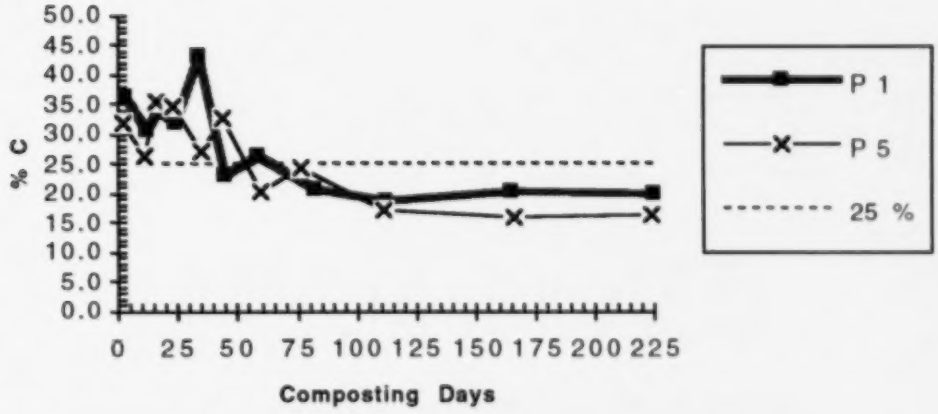


Figure 4.24 **% C vs Composting Days - Piles 1 and 5**

Med C:N, Low M.C.

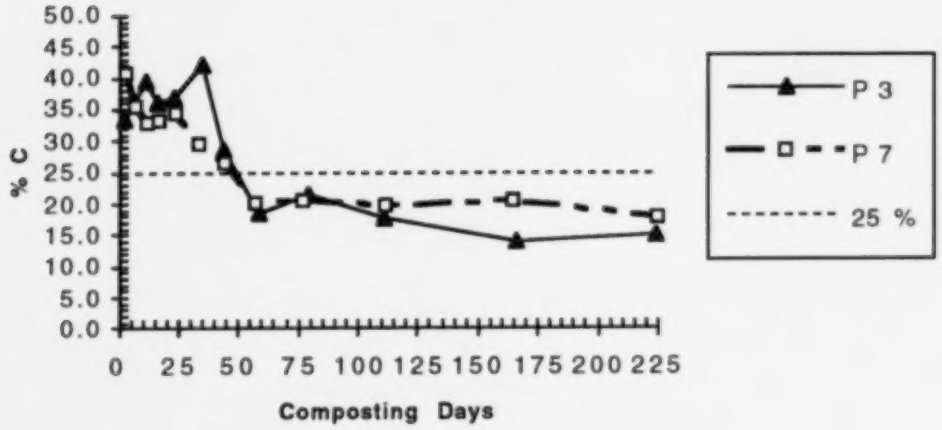


Figure 4.25 % C vs Composting Days - Piles 3 and 7

Med C:N, Hi M.C.

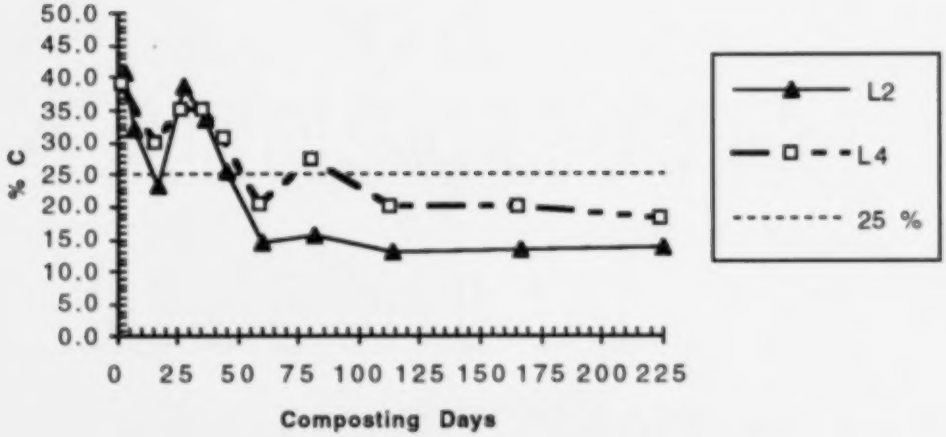


Figure 4.26 % C vs Composting Days - Piles L2 and L4

Low C:N, Low M.C.

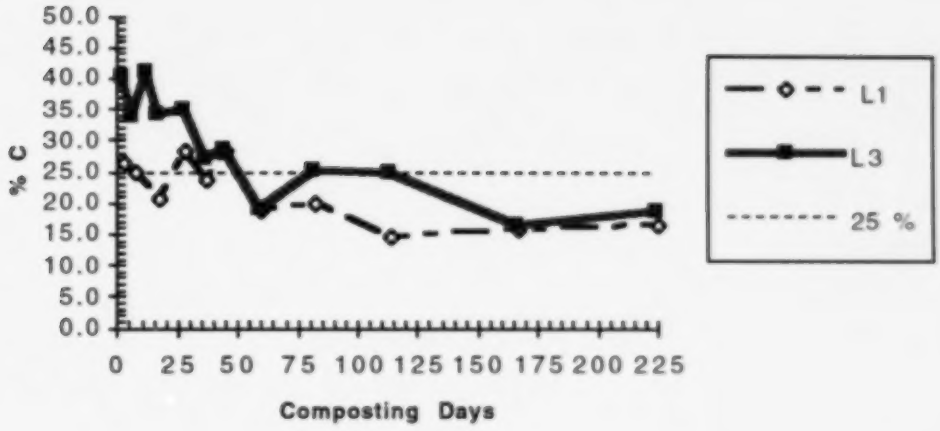


Figure 4.27 **% C vs Composting Days - Piles L1 and L3**

Low C:N, Hi M.C.

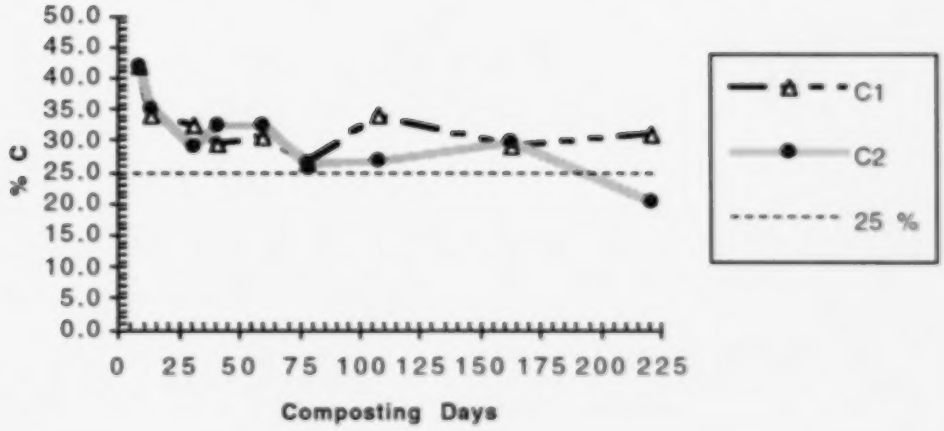


Figure 4.28 **% C vs Composting Days - Piles C1 and C2**

Control Piles

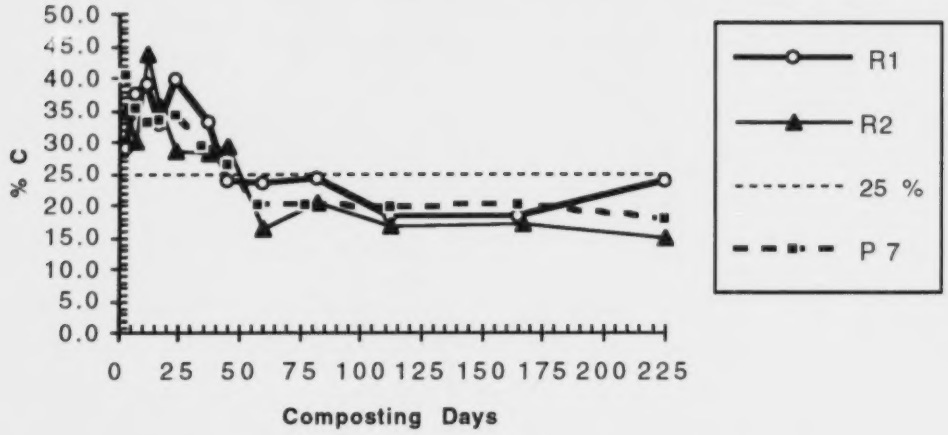


Figure 4.29 **% C vs Composting Days - Piles 7, R1 and R2**
Med C:N, HI M.C.
Replicates

The values for the % change in total carbon content for each compost pile section are highly dependent on the reliability of the initial and final determinations for % C. The average % volatile solids values and their standard deviations are listed in Table A.1 in Appendix A. The % C values were determined by dividing the % volatile solids values by 1.8 as indicated in section 3.2.3.3.

Multiple samples were also collected for piles 1 to 8 and R1 and R2 to test for spatial differences in the compost material within the respective piles. The % volatile solids (% VS) parameter was used to evaluate the spatial differences in the compost material within a pile. Based on the multiple sample % VS results outlined in Table A.2, the samples collected for pile 2 on September 26, 1992 and pile 7 on October 10, 1992 showed the largest variation in % VS. The analysis of variance (ANOVA) method was used to test the null hypothesis (H_O) that the mean % VS values at the different locations within a pile are not different. The alternate hypothesis (H_A) is that the mean % VS values at the different locations within a pile are not the same. The results of the two ANOVA tests summarized in Table A.3 indicated the null hypothesis could not be rejected. Although statistically the mean % VS values

at the different locations within the respective piles were not considered different, there was a significant amount of variability in the pile % VS values as indicated in Table A.2. For example, the mean % VS value for the multiple samples collected on September 26, 1992 for pile 2 was 34.81 $\pm$ 7.94 with a standard error of 3.44. The calculated confidence interval values for pile 2 on this sample date represents a $\pm$22.80% of the pile mean value. The 95% confidence interval for most of the piles (as expressed as a percentage of the pile mean % VS values) were > $\pm$10.00%. This variability might be explained by the heterogeneity of the pile material or errors introduced by the method of volatile solids determination. To ensure samples were not contaminated from materials of adjacent pile sections compost samples were randomly selected from the middle third of each pile section.

Table 4.6 outlines the % carbon values for the initial and final samples for the various compost pile sections.

Table 4.6 - Pile % Carbon values - Solid samples

Pile No.	Pile Designation	% C Initial values	% C Final values
1	Med C:N, Low M.C., Low Por.	36.2	20.0
3	Med C:N, Hi M.C., Low Por.	33.4	15.2
5	Med C:N, Low M.C., Hi Por.	31.9	16.1
7	Med C:N, Hi M.C., Hi Por.	40.6	17.8
R 1	Med C:N, Hi M.C., Hi Por.	29.1	24.0
R 2	Med C:N, Hi M.C., Hi Por.	35.0	15.0
2	Hi C:N, Low M.C., Low Por.	23.2	13.3
4	Hi C:N, Hi M.C., Low Por.	33.5	15.8
6	Hi C:N, Low M.C., Hi Por.	44.6	19.9
8	Hi C:N, Hi M.C., Hi Por.	33.5	8.9
L 1	Low C:N, Hi M.C., Low Por.	26.5	16.5
L 2	Low C:N, Low M.C., Low Por.	40.9	13.8
L 3	Low C:N, Hi M.C., Hi Por.	40.2	18.8
L 4	Low C:N, Low M.C., Hi Por.	39.0	18.1
C1	Control Pile	42.1	30.9
C2	Control Pile	42.1	20.4

The initial mean % C values for the high, medium and low C:N ratio piles were generally quite similar. The high C:N ratio piles 2, 4, 6 and 8 had a mean % C value of 33.7 with a standard deviation of 8.7. Pile section 2 had an initial % C content of 23.2, the lowest value of all the pile sections. The medium C:N ratio piles had a mean % C value of 34.4 with a standard deviation of 3.9. The low C:N ratio piles had the highest mean % C value of 36.7 with a standard deviation of 6.8. The high and medium C:N ratio piles were expected to have higher % C values due to the addition of straw. The mixing of 2 additional front end loader buckets of wheat straw to pile sections 4 and 6 (day 18), 2 and 8 (day 19) on August 17, 1992 did not seem to increase the % C values for the August 23, 1992 samples. The mean % C value for the high C:N ratio piles was 34.6 with a standard deviation of 1.5, compared to a mean and standard deviation of 34.4 and 3.8 for the medium C:N ratio piles. The initial % C results may be influenced by the heterogeneity of the mixed materials, sampling and test methods, or the amount of straw added to the piles.

The final % C contents also influence the % change in total carbon values. For example, pile R1 had a relatively high final % C content of 24.0%. compared to values of 17.8% and 15.0% for pile sections 7 and R2 which had the same treatment design. The high final % C content for pile R1 may be due to the possible contamination of the compost sample with the compost cover material. The burlap material used to separate the experimental compost material from the compost cover decomposed in most piles making it difficult to collect a true representative sample. This high final % C content for pile R1 results in a very low value for the % change in the total carbon.

The final % C contents for the control piles taken on day 221 varied considerably. The values for pile sections C1 and C2 were were 30.9% and 20.4% respectively. The most likely explanation for the large difference is sampling or testing errors. The % C content for piles C1 and C2 were 29.1% and 29.6% for the samples taken on day 163. The average pile temperatures for both C1 and C2 during the period between day 163 and day 221 were below 10^0C. These

low temperatures hindered the decomposition of the organic matter. It is unlikely the change in carbon content for pile section C2 observed during the period between day 163 and day 221 can be attributed to decomposition.

Given the results of the initial and final % C values, the % decrease in carbon content for the pile sections is not considered a reliable response indicator for this experiment. The % decrease in TOC of water extracts is a more reliable response factor because it better reflects the carbon available for microbial utilization.

4.1.2.2 Total Organic Carbon (TOC) - Compost Water Extracts

The TOC values for the various compost pile sections generally followed a decreasing trend throughout the composting period, with most of the decrease observed during the first 50 to 75 days of the process when the more available organic constituents are decomposed. The overall mean % change in TOC value was 73.9% with a standard deviation of 9.6. The highest % change in TOC was 84.8% for high C:N ratio pile 8 and the lowest was 53.1% for low C:N ratio pile section L4. Figures 4.30 to 4.36 display the TOC content (water extracts) versus the composting period for the various pile sections. The piles are organized according to their experimental C:N ratio and moisture levels.

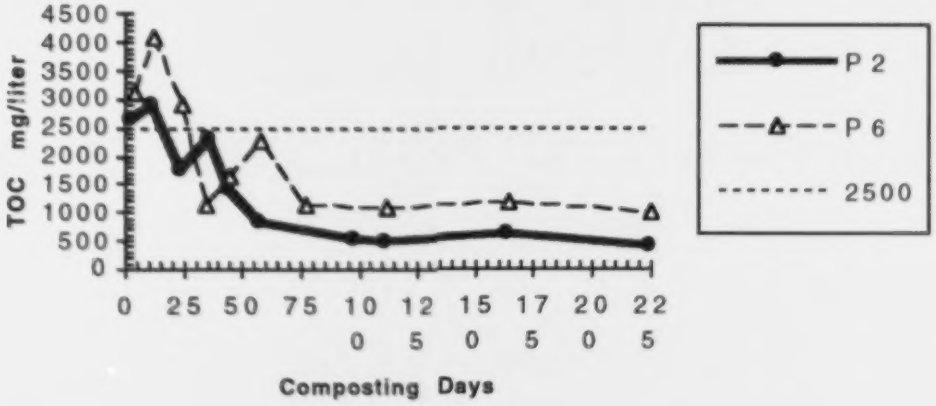


Figure 4.30 **TOC vs Composting Days - Piles 2 and 6**

Hi C:N, Low M.C.

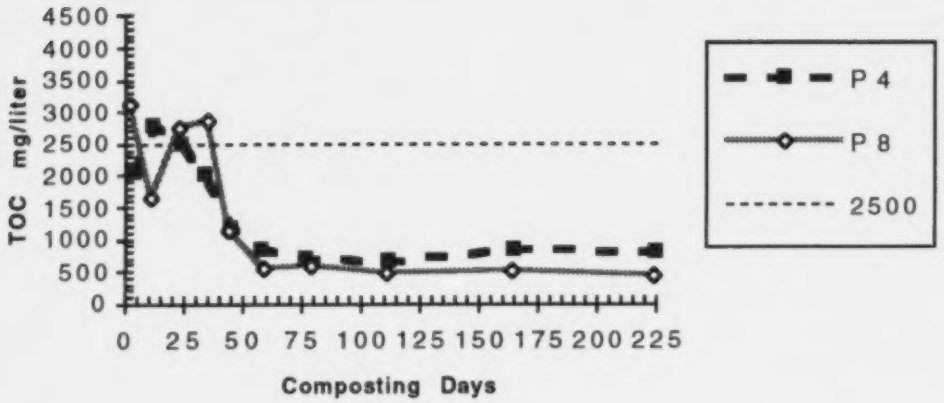


Figure 4.31 TOC vs Composting Days - Piles 4 and 8

Hi C:N, Hi M.C.

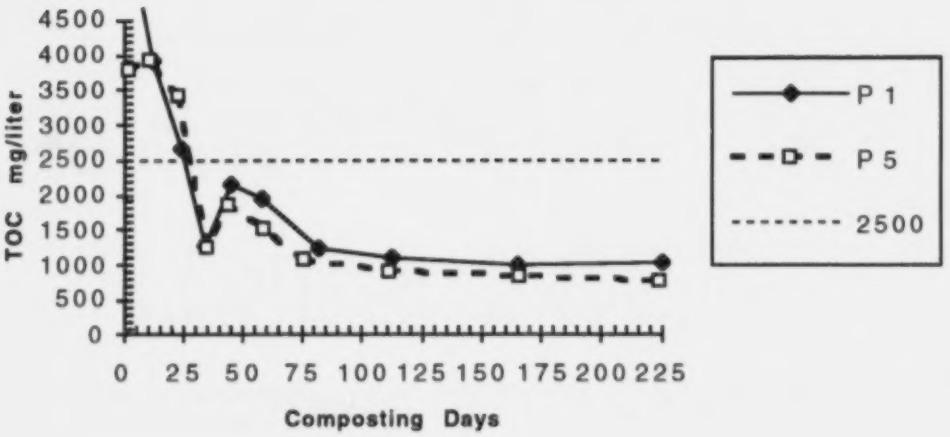


Figure 4.32 TOC vs Composting Days - Piles 1 and 5

Med C:N, Low M.C.

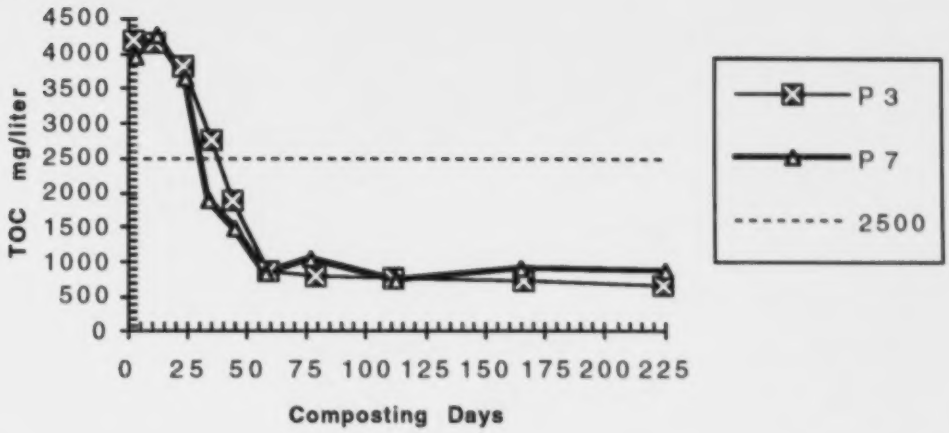


Figure 4.33 TOC vs Composting Days - Piles 3 and 7

Med C:N, Hi M.C.

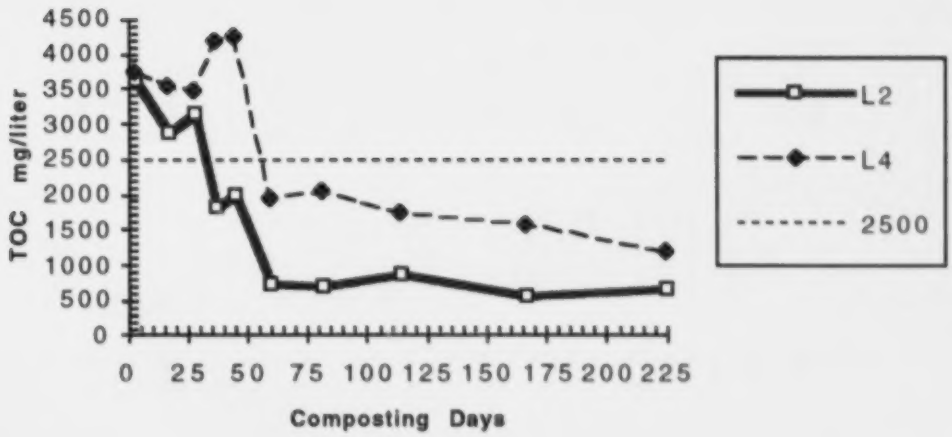


Figure 4.34 TOC vs Composting Days - Piles L2 and L4

Low C:N, Low M.C.

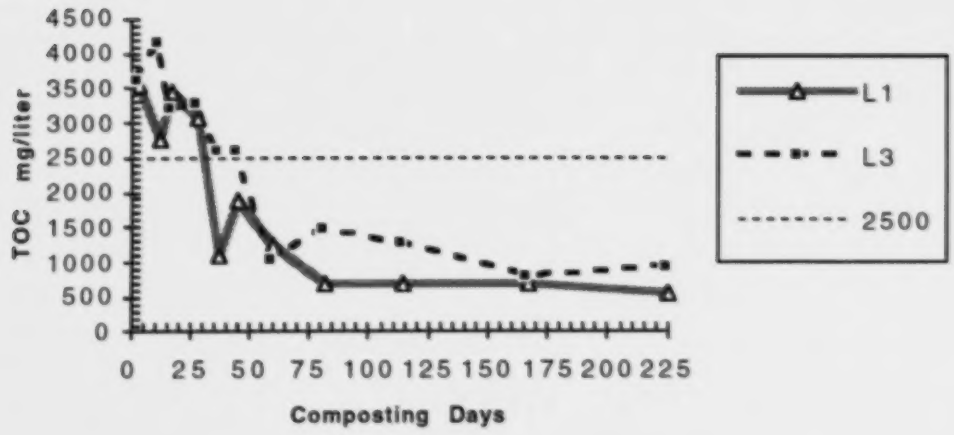


Figure 4.35 TOC vs Composting Days - Piles L1 and L3
Low C:N, Hi M.C.

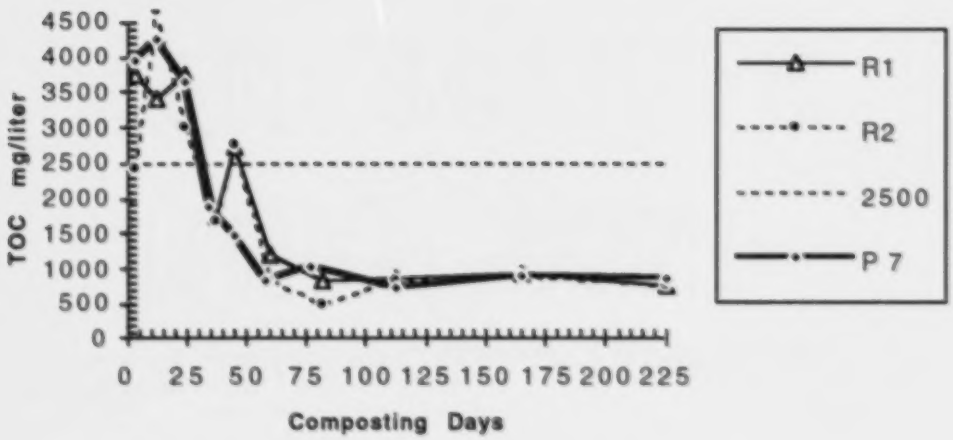


Figure 4.36 TOC vs Composting Days - Piles 7, R1 and R2
Med C:N, Hi M.C.
Replicates

The TOC values of the different piles sections fluctuated more during the first 36 days of the process and usually increased from the initial values. Piles 2, 4, 5, 6, 7, R2 and L3, for example, had higher TOC values on the samples taken on composting days 11 and 12, than determined from the initial samples. Riffaldi *et al* (1988) found the water soluble components initially increased during the first five days of composting a mixture of wastewater sludge from a paper factory and chopped straw. They attributed the initial increase to the increasing rate of decomposition by the microorganisms and they suggested the hydrolysis and solubilization of the complex substances initially predominated over mineralization and immobilization processes. The water soluble components of the compost water extract gradually decreased due to the microbial activity.

The values for the % change TOC content for each compost pile section are also highly dependent on the reliability of the initial and final determinations for TOC. The standard deviation of the average TOC value for multiple injections can be found in Appendix C.1. Table 4.7 outlines the TOC values for the initial and final samples for the various compost pile sections.

Table 4.7 - Pile TOC values - Water Extracts

Pile No.	Pile Designation	Initial TOC values mg/liter	Final TOC values mg/liter
1	Med C:N, Low M.C., Low Por.	5499.5	1017.8
3	Med C:N, Hi M.C., Low Por.	4137.7	649.6
5	Med C:N, Low M.C., Hi Por.	3778.1	752.0
7	Med C:N, Hi M.C., Hi Por.	3940.6	857.2
R1	Med C:N, Hi M.C., Hi Por.	3731.3	753.2
R2	Med C:N, Hi M.C., Hi Por.	2412.4	756.6
2	Hi C:N, Low M.C., Low Por.	2644.2	402.1
4	Hi C:N, Hi M.C., Low Por.	2053.7	793.9
6	Hi C:N, Low M.C., Hi Por.	3137.0	997.0
8	Hi C:N, Hi M.C., Hi Por.	3124.7	438.4
L1	Low C:N, Hi M.C., Low Por.	3536.3	571.4
L2	Low C:N, Low M.C., Low Por.	3608.8	646.1
L3	Low C:N, Hi M.C., Hi Por.	3602.1	944.4
L4	Low C:N, Low M.C., Hi Por.	3735.9	1195.0
C1	Control Pile		
C2	Control Pile		

The high C:N ratio piles 2, 4, 6 and 8 have a mean TOC value of 2739.9 with a standard deviation of 511.8. The medium C:N ratio piles have the highest mean TOC value of 3916.6 with a standard deviation of 987.0. The low C:N ratio piles have a mean TOC value of 3620.8 with a standard deviation of 83.4. As expected, the high C:N ratio piles had lower TOC values because straw has a lower relative proportion of water-soluble organic matter. Theoretically, the low C:N ratio piles should have had the highest initial TOC values because grass has a high relative proportion of water soluble organic matter. The differences in the mean values for the low and medium C:N ratio pile sections may be the result of heterogeneity of the compost material, sampling and or testing methods and procedures.

The % change in TOC values provide a relative indication of the level of maturity of the various piles and serves as a response

variable in factorial design calculations to evaluate the influence of the key operational parameters on the decompostion rate. A more absolute indicator of maturity is the organic carbon to organic nitrogen ratio of water extracts. The following section discusses the organic carbon to organic nitrogen results for the various pile sections.

4.4.1.2.3 $C:N_W$ ratio - Water Extracts

The organic carbon/organic nitrogen ($C:N_W$) values for the various pile sections fluctuated widely throughout the composting period although pile sections 2, 3, 4, 7, and L1 generally followed a decreasing trend. Garcia *et al.* (1991b) found the water soluble carbon/organic nitrogen ratio decreased considerably during the process for various mixtures of organic wastes consisting of aerobic sewage sludge, city refuse, grape debris and peat residue. Figures 4.37 to 4.43 show the $C:N_W$ values versus the composting period for the various pile sections. The pile sections are organized according to their experimental C:N ratio and moisture levels.

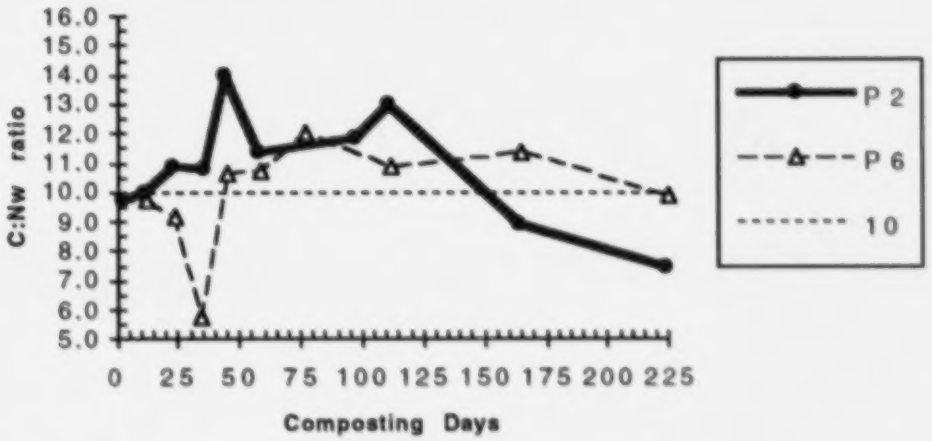


Figure 4.37 **$C:N_W$ vs Composting Days - Piles 2 and 6**

Hi C:N, Low M.C.

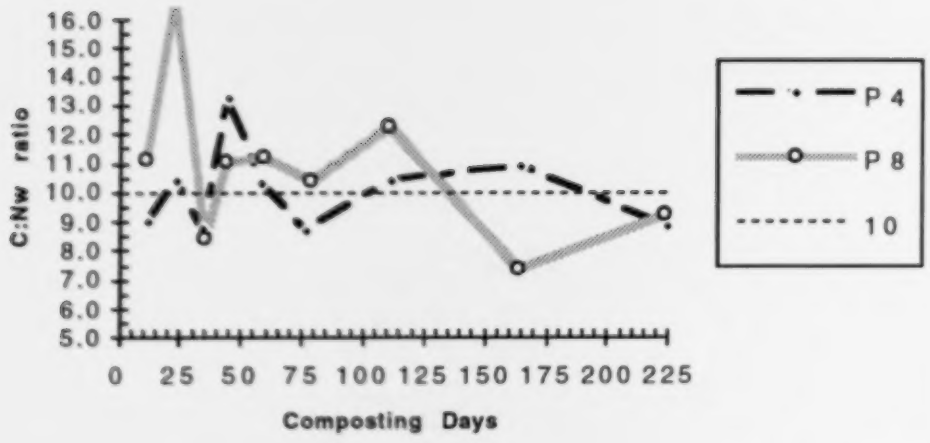


Figure 4.38 C:N_W vs Composting Days - Piles 4 and 8

Hi C:N, Hi M.C.

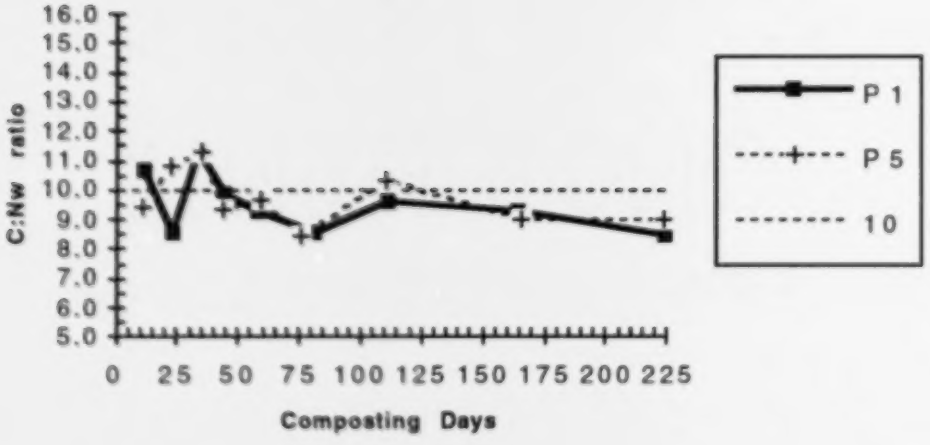


Figure 4.39 C:N_W vs Composting Days - Piles 1 and 5

Med C:N, Low M.C.

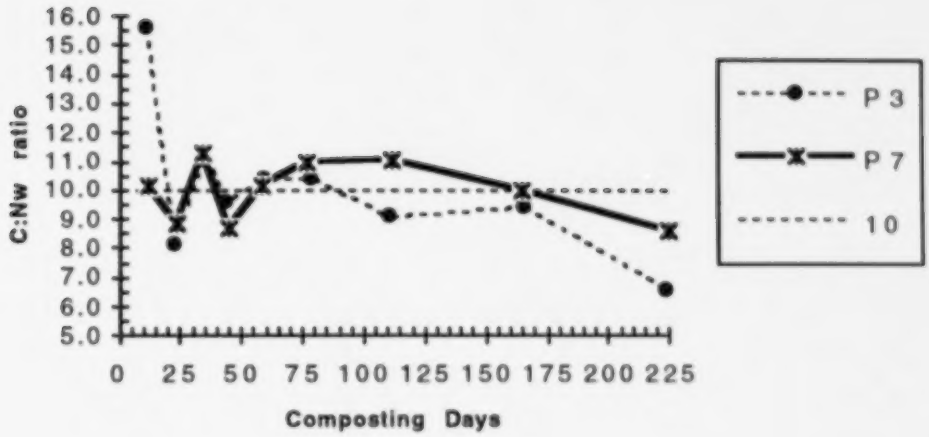


Figure 4.40 C:N_W vs Composting Days - Piles 3 and 7

Med C:N, Hi M.C.

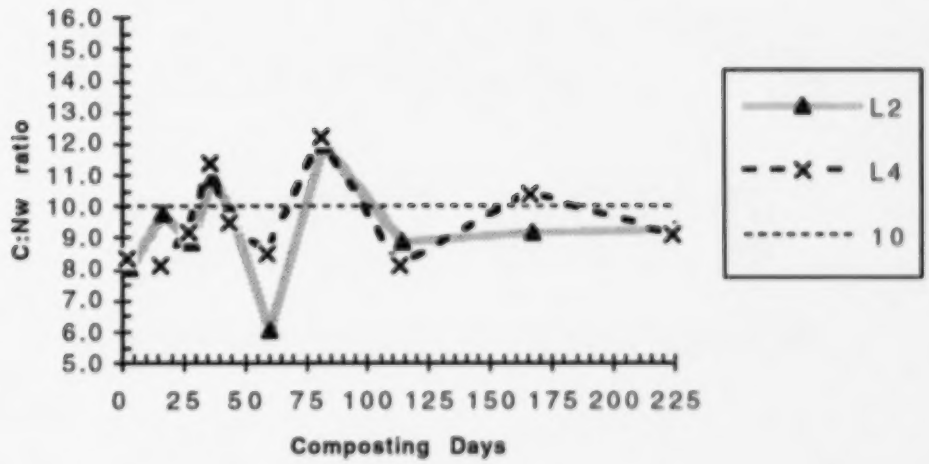


Figure 4.41 C:N_W vs Composting Days - Piles L2 and L4

Low C:N, Low M.C.

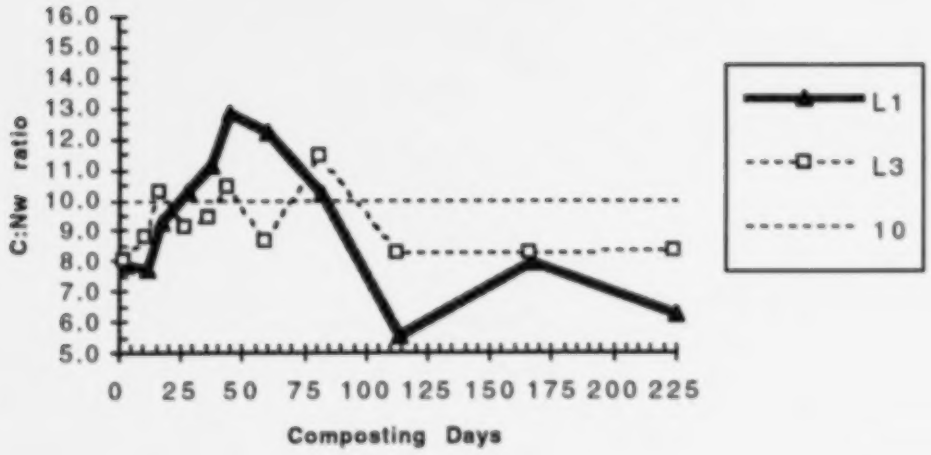


Figure 4.42 $C:N_W$ vs Composting Days - Piles L1 and L3

Low C:N, Hi M.C.

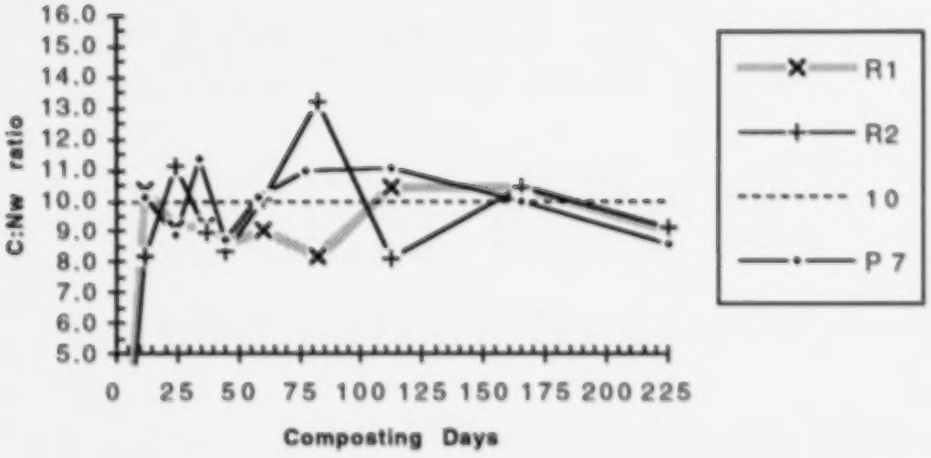


Figure 4.43 $C:N_W$ vs Composting Days - Piles R1 and R2 and P 7

Med C:N, Hi M.C.

Replicate Piles

The final $C:N_w$ ratio values for compost is considered an absolute indicator of compost maturity. Several authors have indicated a final $C:N_w$ ratio value between the 5 and 6 is as an absolute indicator of mature compost (Chanyasak and Kubota 1981; Chanyasak *et al.* 1982; Hirai *et al.* 1983; Riffaldi *et al.* 1988; Garcia *et al.* 1991). Table 4.8 outlines the initial and final $C:N_w$ values for the experimental piles. The initial $C:N_w$ values are from the August 11th and 16th, 1992 samples. There was not enough compost material remaining from the first samples to develop compost water extracts.

Table 4.8 - Pile Initial and Final $C:N_w$ ratios - Water Extracts

Pile No.	Pile Designation	Initial $C:N_w$	Final $C:N_w$
1	Med C:N, Low M.C., Low Por.	10.60	8.44
3	Med C:N, Hi M.C., Low Por.	15.57	6.60
5	Med C:N, Low M.C., Hi Por.	9.39	9.03
7	Med C:N, Hi M.C., Hi Por.	10.12	8.59
R1	Med C:N, Hi M.C., Hi Por.	10.36	9.01
R2	Med C:N, Hi M.C., Hi Por.	8.21	9.13
2	Hi C:N, Low M.C., Low Por.	9.97	7.50
4	Hi C:N, Hi M.C., Low Por.	9.00	8.80
6	Hi C:N, Low M.C., Hi Por.	9.77	9.88
8	Hi C:N, Hi M.C., Hi Por.	11.09	9.23
L1	Low C:N, Hi M.C., Low Por.	7.75	6.25
L2	Low C:N, Low M.C., Low Por.	8.86	9.24
L3	Low C:N, Hi M.C., Hi Por.	8.84	8.33
L4	Low C:N, Low M.C., Hi Por.	8.13	9.13

Initial values for piles L2 and L4 (92-08-16 sample)
Initial values for all other piles (92-08-11 sample)

The sole purpose for determining the final $C:N_w$ ratio values was to identify which piles matured first. None of the final $C:N_w$ ratio values were between 5 and 6, the range indicated for mature compost. The overall mean final $C:N_w$ value for the experimental pile sections was 8.51 with a standard deviation of 1.0. The overall average initial (August 11, 1992 samples) $C:N_w$ value for the experimental piles was 9.83 with a standard deviation of 1.92. The final $C:N_w$ values were generally lower than the initial values. Pile section 3 had the lowest final value of 6.6, although piles L2 and 6 had values of 6.1 and 5.7 on days 60 and 34. The final $C:N_w$ for pile sections L2 and 6 were 9.2 and 9.9. The $C:N_w$ ratios do not provide an absolute indication of which pile sections matured first.

The experimental and literature $C:N_w$ ratios differences may be due to the type of organic materials composted. The literature studies involving water extracts from air dried compost samples tested mature composts from a variety of organic mixtures but not grass and grass and straw composts. Grebus (1992) tested water extracts from fresh mature yard waste compost samples and found the $C:N_w$ ratios to be higher than the literature values of between 5 and 6. The results obtained in this study may be representative of the true organic carbon to organic nitrogen ratios of mature grass and grass and straw composts. The most likely explanation for the differences in literature and experimental results are sample preparation and testing errors. For example, the final $C:N_w$ values for pile sections 6 and L2 were much higher than the minimum values observed on days 34 and 60, respectively. The next section outlines the results of a secondary measure of organic degradation, the % increase in the compost dry bulk density.

4.1.2.4 Dry Bulk Density

As expected, the dry bulk density (DBD) of the various piles increased throughout the composting period, with most of the increase observed during the first 112 days, the active phase of the process and then remained fairly constant or increased slightly during the remaining 113 days or maturation phase. Low C:N ratio pile L1 had the highest % increase in DBD of 68.3%, while the lowest

increase of 34.4% was observed for pile section 8. The mean % increase in DBD for the experimental pile sections was 55.3 with a standard deviation of 9.9 (from August 23, 1992 sample). This compares favorably to the mean value of 59.4% with a standard deviation of 8.0 observed by Fleming (1991) in the composting of mixtures of green waste, leaves and wood wastes in Florida. Control piles C1 and C2 had a lower mean % increase in dry bulk density of 36.4% with a standard deviation of 3.0 potentially indicating the organic materials did not degrade as much as the experimental piles. Multiple sample bulk density measurements were taken for piles 4 and 6 on October 16, 1992 to determine variability in bulk density measurements. Four wet bulk density measurements were taken for each pile. The average wet bulk density value for pile 4 was 434.0 Kg/m^3 with a standard deviation of 35.37. Pile 6 had an average wet bulk density value of 654.8 Kg/m^3 with a standard deviation of 36.29. Figures 4.44 to 4.51 display the DBD versus the composting period for the various pile sections. The pile sections are organized according to their experimental C:N ratio and moisture levels.

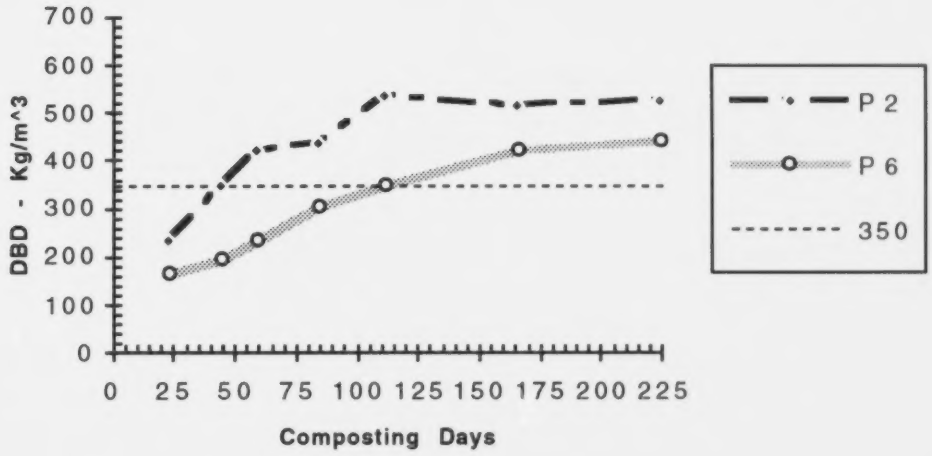


Figure 4.44 **DBD vs Composting Days - Piles 2 and 6**

Hi C:N, Low M.C.

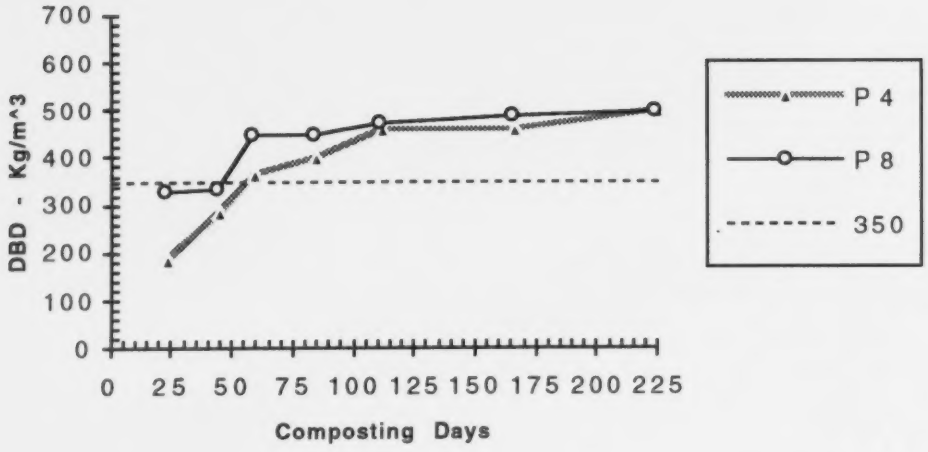


Figure 4.45 DBD vs Composting Days - Piles 4 and 8
Hi C:N, Hi M.C.

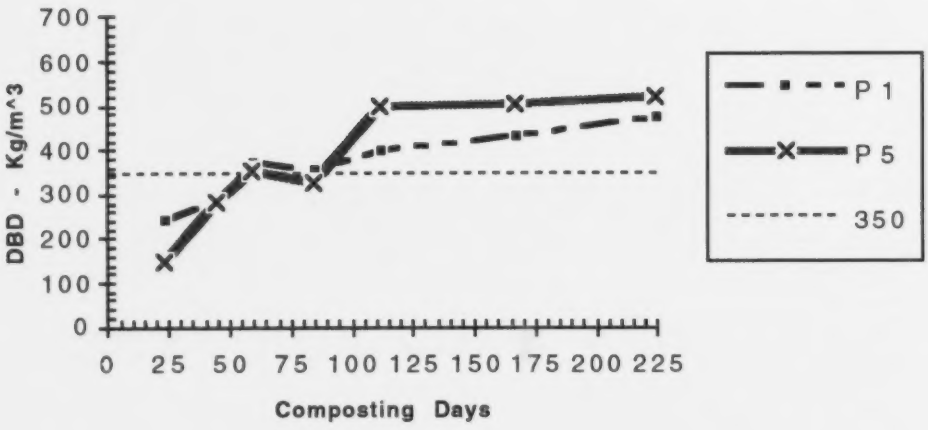


Figure 4.46 DBD vs Composting Days - Piles 1 and 5
Med C:N, Low M.C.

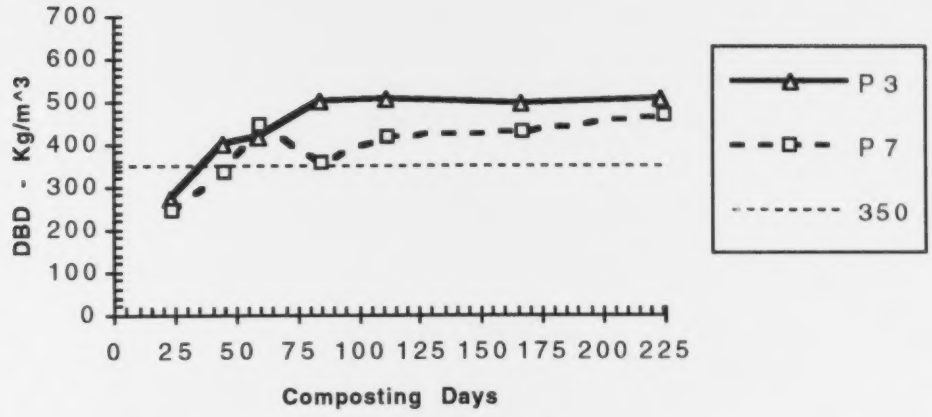


Figure 4.47 DBD vs Composting Days - Piles 3 and 7
Med C:N, Hi M.C.

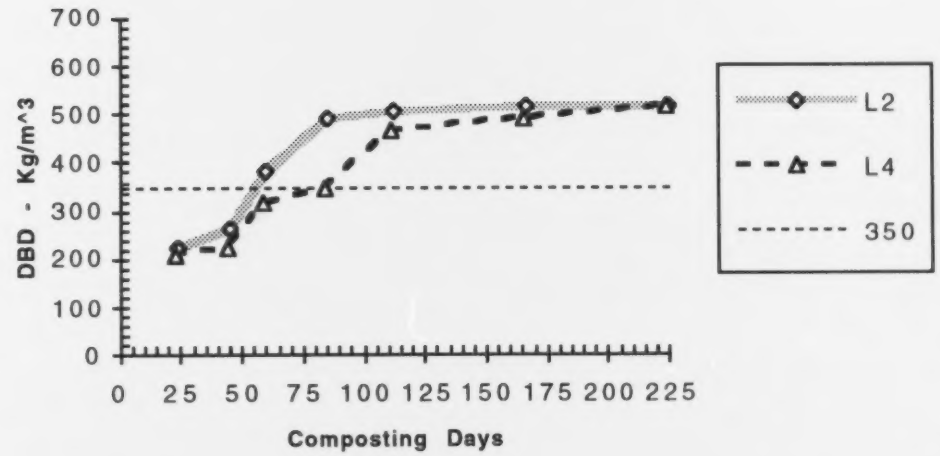


Figure 4.48 DBD vs Composting Days - Piles L2 and L4
Low C:N, Low M.C.

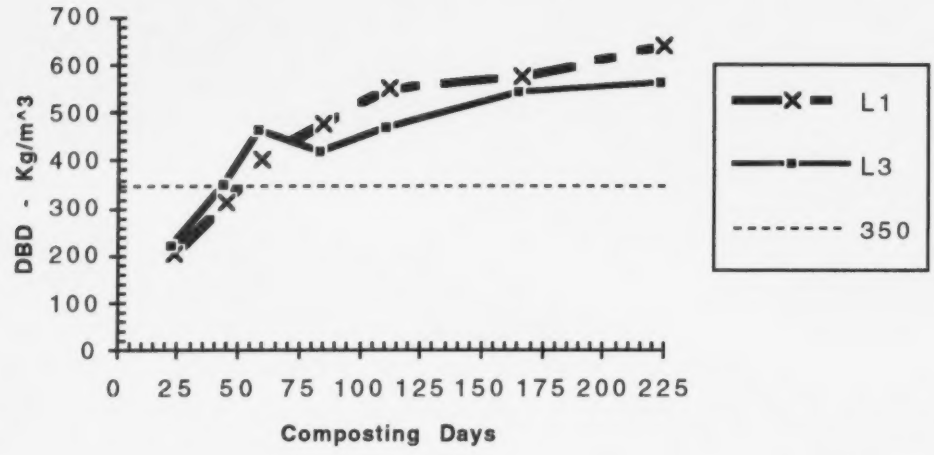


Figure 4.49 DBD vs Composting Days - Piles L1 and L3
Low C:N, Hi M.C.

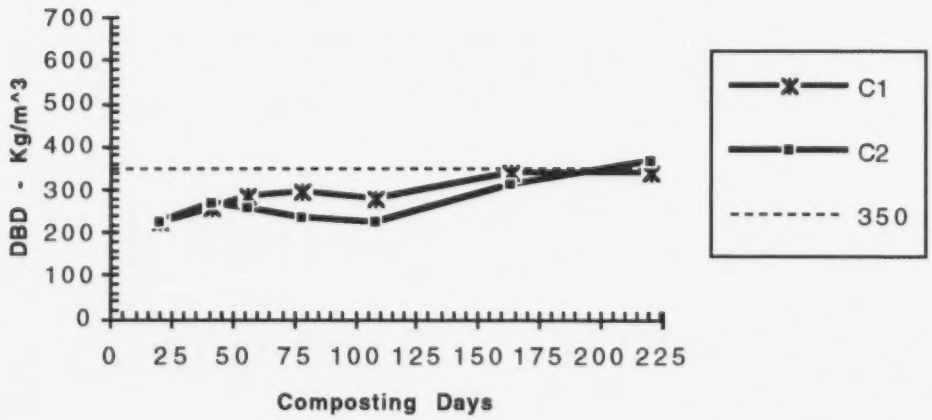


Figure 4.50 DBD vs Composting Days - Piles C1 and C2
Control Piles

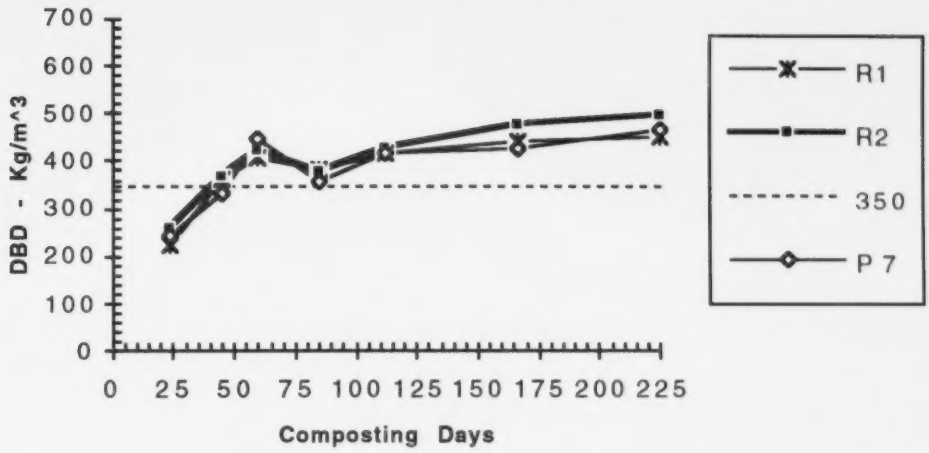


Figure 4.51 **DBD vs Composting Days - Piles 7, R1 and R2**
Med C:N, Hi M.C.
Replicate Piles

Pile sections 4, 5, 6, 7, 8, L3 and L4, R1 and R2, which had wood chips added to adjust porosity, generally have lower values of dry bulk density than the piles with the same experimental moisture and C:N levels. Wood chips were added to pile 5, on day 70 and piles 6, 7, on day 71 and to piles 8, L3 and L4 on day 77 and Piles R1 and R2 on day 78. The wood chips are less dense than the existing compost mixtures so the lower dry bulk density values for the porosity adjusted piles are expected. Table 4.10 outlines the dry bulk density values for the August 23, 1992 samples and the final samples for the various compost pile sections.

Table 4.9 - Pile Dry Bulk Density values (DBD)

Pile	Pile Designation	DBD Kg/m^3 92-08-23	DBD Kg/m^3 93-03-13
1	Med C:N, Low M.C., Low Por.	237.7	470.7
3	Med C:N, Hi M.C., Low Por.	270.5	504.4
5	Med C:N, Low M.C., Hi Por.	148.3	517.1
7	Med C:N, Hi M.C., Hi Por.	245.3	467.7
R1	Med C:N, Hi M.C., Hi Por.	225.8	451.0
R2	Med C:N, Hi M.C., Hi Por.	256.6	495.0
2	Hi C:N, Low M.C., Low Por.	232.3	526.1
4	Hi C:N, Hi M.C., Low Por.	184.9	493.9
6	Hi C:N, Low M.C., Hi Por.	162.3	443.0
8	Hi C:N, Hi M.C., Hi Por.	326.6	496.2
L1	Low C:N, Hi M.C., Low Por.	202.8	640.6
L2	Low C:N, Low M.C., Low Por.	222.8	516.9
L3	Low C:N, Hi M.C., Hi Por.	219.7	559.4
L4	Low C:N, Low M.C., Hi Por.	207.9	518.3
C1	Control Pile	221.2	336.9
C2	Control Pile	226.0	367.8

The dry bulk density values for the high C:N ratio piles on August 23, 1992 varied from 162.3 Kg/m^3 for pile 6 to a high value of 326.6 Kg/m^3 for pile section 8. The mean value was 226.5 Kg/m^3 with a standard deviation of 72.8. The medium C:N ratio piles have a mean DBD value on August 23, 1992 of 230.7 Kg/m^3 with a standard deviation of 43.2. The low C:N ratio piles have a mean value of 213.3 Kg/m^3 with a standard deviation of 9.5. The large variation in DBD values observed for the high C:N ratio piles on August 23, 1992 may be explained by the heterogeneity of the mixtures of straw and grass.

The mean final DBD for the high C:N piles was 489.8 Kg/m^3 with a standard deviation of 34.5. The medium C:N ratio piles had a similar final value of 484.3 Kg/m^3 with a standard deviation of 25.2. The highest mean final DBD of 558.8 Kg/m^3 with a standard

deviation of 58.0 was observed for the low C:N ratio piles. The dry bulk densities were comparable to values observed by Fleming (1991). In her study, the initial and final mean DBD were 259.6 Kg/m^3 and 639.4 Kg/m^3 with standard deviations of 87.3 and 56.8.

The % increase in DBD provides a relative indication of the level of maturity of the various piles and serves as a response variable in factorial design calculations to evaluate the influence of the key operational parameters on the decomposition rate. Although it is not considered a primary indicator of compost maturity, it may be useful in the confirmation of the results of more recognized maturity parameters.

4.1.3 Factorial Design Results

Because the experimental moisture levels were not able to be maintained the design matrix was adjusted to reflect the actual moisture levels measured in the different compost piles. The adjusted factorial design matrices are referred to as botched factorials. The +1 and -1 levels for the moisture content variable are replaced by values representing the actual pile moisture content as a percentage of the planned experimental levels. For example, the weighted average moisture content for pile 2 for the full composting period was 27.0% which is 0.68 of the planned experimental level of 40%. Instead of +1 and -1 levels ± 0.68 is used in the design matrix. The factorial design was analysed using the % decrease in TOC and the % increase in dry bulk density for both the active and full composting periods as the response variables. The results for the active composting period reflect the importance of the operational variables during the period when most of the decomposition of organic materials takes place. As stated earlier the % decrease in TOC is considered the most reliable response variable. The % increase in dry bulk density is a secondary and less reliable response variable. The following section summarizes the results of the factorial experiment for both response variables.

4.1.3.1 Factorial Experiment - Results

The results of the factorial design, using % decrease in TOC as the response variable, indicate none of the main effects and their interactions were found to significantly effect the decomposition of the organic materials. Based on the calculated 95% confidence intervals of the regression coefficient ß values, none of the factors are significantly different from zero. All the ß values have both positive and negative confidence interval values, indicating zero is a possible value. The ß values measure the effect of a unit change in the variable on the mean response (Montgomery 1984). The main effects and their interactions represent a change from -1 to +1, a change of 2 units. To calculate the main effects and their interactions, the ß values are doubled. The results of the factorial experiment are shown in Table E.1 in Appendix E. Table 4.10 summarizes the significant factors for both response variables based on the 95% and 90% confidence intervals, as well as the results from the half normal plots.

Table 4.10 - Factorial Experiment - Significant Effects

	Significant Effects and Interactions					
Response Variable	% Decrease in TOC			% Increase in Dry Bulk Density		
Period	**95% CI**	**90% CI**	**Half Normal Plot**	**95% CI**	**90% CI**	**Half Normal Plot**
Full	None	13 23 123	13 123	23	23	3 123
Active	None	None	2 12 13	23	23	3 13 23

The confidence interval results are considered more reliable because the results of the half normal plot are dependent upon how the straight line is drawn through the points. Although the 95 %

confidence interval results, using % decrease in TOC as the response variable, indicate no factor is significant, results from the 90 % confidence interval calculations and the half normal plots for both response variables provide some indication that some factors marginally influenced the decomposition process. In addition, ranking the effects from the highest to lowest value after normalization also provides a measure of relative importance. The higher the normalized value the larger the effect on the decomposition rate. The effects are normalized by dividing the value of the effect by the standard error at the 5% significance level.

For the full composting period, the 90% confidence interval calculations of the ß values for the response variable % decrease in TOC, suggest the interactions 13 (C:N ratio-Porosity), 23 (MC-Porosity) and 123 (C:N ratio-MC-Porosity) marginally influenced the decomposition of the organic materials. The results of the half normal plot also indicate the 13 and 123 interactions are significant. The factorial design results, using % increase in dry bulk density as the response variable, found the 23 interaction (MC-Porosity) to be significant. Table 4.11 summarizes the rankings of the effects for both response variable factorials for the full composting period.

Table 4.11 - Ranking of Effects - Full Period

% Decrease in TOC			% Increase in Dry Bulk Density		
Effects	**Value**	**Value/S.E.**	**Effects**	**Value**	**Value/S.E.**
23	-9.14	-4.60	23	-13.77	-5.58
123	-12.16	-4.56	1	-8.82	-3.36
13	-8.2	-3.90	12	-10.70	-3.22
3	3.24	2.02	2	-6.57	-2.66
12	4.46	1.68	123	-8.70	-2.62
1	0.99	0.46	13	-5.11	-1.96
2	-0.27	-0.14	3	-1.27	-0.64

Interactions 23 and 123 and 13 have the highest values of the normalized effects for the % decrease in TOC factorial. The 23 interaction has the highest value of the normalized effects for the dry bulk density factorial. The negative value for the 23 effect for the DBD factorial indicates, this effect has a negative influence on the increase in dry bulk density. A negative value for an effect for the TOC factorial indicates the effect increases the percent decrease in TOC. Based on the overall results of the 90% confidence intervals, half normal plots and rankings, there are indications that the 13, 23 and 123 interactions marginally influenced the decomposition of the organic materials. The factorial results from the TOC response variable are considered more reliable than the dry bulk density results; therefore the conclusions are mainly based on the TOC factorial results.

For the active period, none of the factors were found to influence the decomposition of the organic materials, based on the 90% confidence interval calculations of the ß values for the response variable % decrease in TOC. The half normal plot indicated the main effect 2 (MC) and the interactions 12 (C:N ratio-MC) and 13 (C:N ratio-Porosity) were significant. The dry bulk density factorial confidence interval results indicated the 23 interaction was significant. Table 4.12 summarizes the rankings of the effects for both response variable factorials for the active composting period.

Table 4.12 - Ranking of Effects - Active Period

% Decrease in TOC			% Increase in Dry Bulk Density		
Effects	**Value**	**Value/S.E.**	**Effects**	**Value**	**Value/S.E.**
3	7.78	3.68	23	-15.01	-4.94
13	-10.08	-3.64	1	-7.92	-2.46
23	-8.99	-3.44	2	-6.23	-2.06
1	-6.80	-2.46	13	-6.02	-1.86
123	-5.80	-1.66	12	-7.02	-1.72
2	-1.69	-0.64	3	-3.99	-1.62
12	0.92	0.26	123	-6.3	-1.54

The main effect 3 (Porosity) and interactions 13 and 23 have the highest values of the normalized effects for the % decrease in TOC factorial. The 23 interaction has the highest value of the normalized effects for the dry bulk density factorial. Main effects 1 (C:N ratio) and 2 (MC) have the second and third highest values. Overall the factorial results for the active period do not consistently indicate any of the factors influence the decomposition of the organic materials. The following section discusses the factorial results of the 90% confidence intervals, half normal plots and rankings for the full composting period.

4.1.3.2 Factorial Results Discussion

None of the operational factors were found to significantly effect the decomposition of the organic materials based on the calculated 95% confidence intervals of the ß's for the % decrease in TOC factorial. The 90% confidence intervals, half normal plots and effect rankings for the full composting period provided indications the 13, 23 and 123 interactions marginally influenced the decomposition of the organic materials. The following paragraphs discuss the theoretical importance of these interactions and outlines possible explanations for the factorial results.

The factorial results suggest the operational factors are interelated which is consistent with theory. The 23 interaction (MC-Porosity) which had the highest normalized effect value is considered to have the largest affect on the response variable If the moisture content is too high, the the void space available for air will be reduced. This will result in a lower supply of oxygen which will reduce the rate of biological activity. When the the moisture content is low and the void space available for air is high, the rate of biological activity is also reduced. The flow of air through the void space results in moisture losses and potential cooling of the compost mass. A balance between adequate moisture content and porosity is important for optimizing the decomposition process.

The second and third highest normalized effects based on the TOC factorial results for the full period are the interaction 123 (C:N ratio-MC-Porosity) and 13 (C:N ratio- Porosity). These results

suggest a relationship exists between the moisture content, porosity and the C:N ratio of the materials. A potential explanation may be the variable C:N ratio actually represents the physical nature of the material. The void space in the compost pile is related to the physical nature of the compost materials and not the C:N ratio. Fibrous or bulky materials such as straw and wood chips are able to maintain adequate porosity compared to grass clippings. Golueke (1977) indicated the maximum permissible percent moisture is also a function of the physical nature of the materials. For example, fibrous or bulky materials such as straw and wood chips can absorb relatively large amounts of water and still maintain adequate porosity (Haug 1980).

Finally the lowest normalized effects based on the TOC factorial results for the full period are the main effects 2(MC) and 1(C:N ratio). This may suggest that these factors alone do not influence the decomposition of the organic materials. The normalized effect value for the main effect 3(Porosity) was ranked 4th for the full period and first for the active period for the TOC factorial results. Based on the actual measured porosity values for piles 5, 6, 7, L4, R1, R2 and 8 the porosity generally decreased or remained fairly level for the first porosity measurements after the addition of more wood chips. Possible reasons for the inconsistent results could include errors introduced in measurement, sampling or testing, improper mixing of wood chips, compost cover contamination of the samples or the volume of wood chips added did not significantly alter the porosity of the piles. The most likely explanation are errors introduced in the determination of the porosity measurements. Since there appears to be no standard method of determining compost porosity, the accuracy of the method used in this study can not be determined.

4.1.3.3 Summary and Explanations

In summary, the factorial results based on the calculated 95% confidence intervals of the ß's for the % decrease in TOC factorial found none of the factors influenced the decomposition rate of the organic materials. The 90% confidence intervals, half normal plots and effect rankings for the full composting period provided indications the 13 (C:N ratio-Porosity), 23 (MC-Porosity) and 123 (C:N ratio-MC-Porosity) marginally influenced the decomposition of the organic materials. The results do not support the hypotheses that the operating variables C:N ratio, moisture content and porosity adjustment individually effect the decomposition rate of the organic materials. Possible explanations for these experimental results are: 1) the response variables used in the study were not able to measure the effects, 2) the effect of C:N ratio, M.C. and porosity on degradation did not occur within the ranges tested or 3) the difficulties encountered in maintaining and operating a field level experiment impacted the results. The most likely reasons are the difficulties in maintaining and operating a field level experiment.

For example, the difficulty experienced trying to maintain the experimental moisture levels may have effected the factorial results. It was not possible to maintain the moisture content of the pile sections at the desired levels. For the full composting period the average weighted mean pile moisture content for the high MC piles was 38.6% compared to the experimental level of 60%. For the 40% MC piles, the average weighted mean pile moisture content was 31.2% for the full composting period. The moisture differences may not have been significant enough to create a real difference in the experimental conditions. Although the -1 and +1 levels for the MC variable in the factorial design matrix were adjusted to reflect the calculated values of the pile average weighted moisture contents, these values may not provide a good representation of the actual moisture conditions.

In addition, the amount of straw added to the experimental piles may not have been sufficient enough to create a significant difference in the C:N ratio of the piles. The experimental C:N ratio

levels were based on the number of front end loader buckets instead of the mass of the different organic materials.

4.2 Decomposition

The purpose of monitoring the decomposition of the organic materials for the various compost piles was to: **1**. evaluate and model the biological degradation of these materials over time and provide a tool for optimization of the process; **2**. determine the magnitude and rate of decomposition of the various compost piles.and compare the results with expected behavior. The following sections summarize the decomposition behavior of the experimental compost piles and compares the results to a physical model proposed by Haug (1980).

4.2.1 Decomposition Modelling

Determining the overall reaction rate for the active composting period for the various experimental piles may be useful in identifying differences and process optimization opportunities. Generally the decomposition rate of organic residues especially in soils is considered to follow first order rate kinetics (Paul and Clark 1989). In this study, the parameters % total carbon (% C) in solid compost samples and TOC of compost water extracts were used as measures of the degradation of the organic materials. The measured % C values reported in this study includes the carbon content of substrate as well as biomass. The actual substrate % C is usually determined by subtracting the carbon content of the biomass.

The kinetic rates for the decomposition of the organic materials can be calculated by determining the slope of the line for the different plots of substrate parameters versus time. Instead of plotting the data, linear regression techniques using the least-squares method were used to determine the slope and R^2 value of the fitted line. The R^2 value is the square of the Pearson product moment correlation coefficient. The slope of the fitted line of substrate concentration versus time determined the zero order kinetic rate. For first order kinetics, the slope of the ln of % C and ln of TOC versus time determined the reaction rate constants. The

slope of the fitted line of 1/% C and 1/TOC versus time determined the second order kinetic rates. Table 4.13 on the following page summarizes the modelling results for % C of compost solid samples.

The zero order model has the lowest R^2 value of 0.68 while the average R^2 value for the second order model was highest at 0.76. The first order R^2 value was slightly lower than the second order model at a value of 0.74. The calculated R^2 value is a measure of how well the plotted plots fit the straight line relationship. The closer the R^2 value is to 1.0 the better the data fits the straight line relationship. An analysis of variance test was used to statistically determine, if the average R^2 values for the different models are significantly different. The results outlined in Table F.1 indicated, that collectively there was a difference somewhere in the data of the three groups, but a group by group comparison using the Student-Newman-Keuls test with a 5% significance level found the zero order average R^2 value was significantly different than the first and second order average R^2 values. There was no significant difference found between the first and second order average values. Based on the comparison of the average R^2 values, the % C data for the experimental piles suggests the decomposition process follows either first or second order kinetics. The first order model is the more likely case because other authors have indicated the composting process and decomposition of plant residues generally follow first order rate kinetics (Paul and Clark 1989; Haug 1993).

Table 4.13 - Rate Constants for % Carbon - solid samples

Active Period- all values up to and including November 19-21, 1992 samples.

Pile No.	Pile Designations	Zero Order k (%C day^{-1})	Zero Order R^2	Zero Order Rank	First Order k (day^{-1})	First Order R^2	First Order Rank	Second Order k (%C^{-1}day^{-1})	Second Order R^2	Second Order Rank
1	Med C:N, Low M.C., Low Por.	-0.1706	0.59	8	0.0064	0.69	8	2.497E-04	0.77	8
2	Hi C:N, Low M.C., Low Por.	-0.1800	0.65	7	0.0040	0.76	14	4.981E-04	0.82	2
3	Med C:N, Hi M.C., Low Por.	-0.2139	0.67	5	0.0080	0.72	4	3.097E-04	0.75	6
4	Hi C:N, Hi M.C., Low Por.	-0.2425	0.81	1	0.0090	0.89	3	3.556E-04	0.95	4
5	Med C:N, Low M.C., Hi Por.	-0.0871	0.68	14	0.0057	0.66	10	2.373E-04	0.69	11
6	Hi C:N, Low M.C., Hi Por.	-0.2256	0.75	4	0.0072	0.83	6	2.438E-04	0.88	9
7	Med C:N, Hi M.C., Hi Por.	-0.0903	0.66	13	0.0070	0.84	7	2.658E-04	0.86	7
8	Hi C:N, Hi M.C., Hi Por.	-0.2346	0.83	3	0.0104	0.87	1	5.115E-04	0.85	1
R1	Med C:N, Hi M.C., Hi Por.	-0.1697	0.66	9	0.0062	0.72	9	2.354E-04	0.77	12
R2	Med C:N, Hi M.C., Hi Por.	-0.2027	0.69	6	0.0079	0.74	5	3.230E-04	0.75	5
L1	Low C:N, Hi M.C., Low Por.	-0.0958	0.55	12	0.0047	0.61	13	2.419E-04	0.65	10
L2	Low C:N, Low M.C., Low Por.	-0.2352	0.66	2	0.0102	0.73	2	4.843E-04	0.77	3
L3	Low C:N, Hi M.C., Hi Por.	-0.1548	0.60	11	0.0051	0.57	12	2.061E-04	0.65	13
L4	Low C:N, Low M.C., Hi Por.	-0.1549	0.67	10	0.0056	0.66	11	1.741E-04	0.51	14
C1	Control Pile	-0.0664	0.23	15	0.0019	0.23	16	5.751E-05	0.22	16
C2	Control Pile	0.3117	0.29	16	0.0037	0.66	15	1.153E-04	0.68	15
	Averages	**-0.1755**	**0.68**		**0.0070**	**0.74**		**0.00031**	**0.76**	

The average % C first order reaction rate constant is 0.0070/day. The rate constants listed in Table 2.7 are generally a few magnitudes higher than determined from the the % C data for the experimental piles. For example, the k values for grass/leaves and grass/cardboard mixtures using first order rate equation for the rate of disappearance of compost mass, ranged from 0.165/day to 0.190/day for Marugg (1993). A possible explanation for these results is the measured % C values of the compost includes not only the amount of carbon in the organic residues and the intermediate products, but also the carbon content of the microbes. The measured % C is higher than actual % carbon of the substrate. As the composting process proceeds, the substrate concentration is decreasing and the biomass concentration increases to a certain point in the process. In the latter stages, the biomass concentration starts to decrease as the amount of available substrate decreases. The calculated decomposition rate using % C is probably lower than the actual rate. If the biomass carbon content was subtracted from the total carbon, the actual decomposition rate could of been calculated.

Table 4.14 summarizes the modelling results for the TOC of compost water extracts.

Table 4.14 - Rate Constants for TOC - water extract

Active Period- all values up to and including November 19-21, 1992 samples.

Pile	Pile Designations	Zero Order k mg $L^{-1}day^{-1}$	Zero Order R^2	Zero Order Rank	First Order k day^{-1}	First Order R^2	First Order Rank	Second Order k L $mg^{-1}day^{-1}$	Second Order R^2	Second Order Rank
1	Med C:N, Low M.C., Low Por.	-32.87	0.62	3	0.0132	0.71	11	6.334E-06	0.74	11
2	Hi C:N, Low M.C., Low Por.	-22.22	0.84	11	0.0174	0.93	4	1.691E-05	0.94	2
3	Med C:N, Hi M.C., Low Por.	-37.94	0.83	1	0.0192	0.86	1	1.211E-05	0.86	5
4	Hi C:N, Hi M.C., Low Por.	-20.19	0.73	13	0.0147	0.82	9	1.228E-05	0.87	4
5	Med C:N, Low M.C., Hi Por.	-30.08	0.72	5	0.0147	0.79	10	8.400E-06	0.84	10
6	Hi C:N, Low M.C., Hi Por.	-23.53	0.56	10	0.0112	0.59	13	6.032E-06	0.58	12
7	Med C:N, Hi M.C., Hi Por.	-35.40	0.56	2	0.0182	0.83	3	1.163E-05	0.88	7
8	Hi C:N, Hi M.C., Hi Por.	-10.95	0.64	14	0.0189	0.75	2	1.855E-05	0.81	1
R1	Med C:N, Hi M.C., Hi Por.	-30.63	0.79	4	0.0174	0.66	5	1.336E-05	0.59	3
R2	Med C:N, Hi M.C., Hi Por.	-29.34	0.58	6	0.0161	0.84	8	9.959E-06	0.85	9
L1	Low C:N, Hi M.C., Low Por.	-28.05	0.75	7	0.0166	0.82	6	1.201E-05	0.85	6
L2	Low C:N, Low M.C., Low Por.	-27.77	0.77	8	0.0162	0.76	7	1.126E-05	0.70	8
L3	Low C:N, Hi M.C., Hi Por.	-26.88	0.77	9	0.0119	0.74	12	5.851E-06	0.65	13
L4	Low C:N, Low M.C., Hi Por.	-22.20	0.60	12	0.0083	0.66	14	3.242E-06	0.72	14
	Averages	**-27.00**	**0.70**		**0.0153**	**0.77**		**0.0000106**	**0.78**	

The zero order model has the lowest R^2 value of 0.70 while the average R^2 value for the second order model was highest at 0.78. The first order R^2 value was slightly lower than the second order model at a value of 0.77. An analysis of variance test was again used to statistically determine, if the average R^2 values for the different models are significantly different. The results indicated that collectively there was a difference somewhere in the data of the three groups but a group by group comparison using the Student-Newman-Keuls test with a 5% significance level found there was no significant difference between the average R^2 values. Based on the comparison of the average R^2 values, the TOC data for the experimental piles suggests the decomposition of the organic materials follows either zero, first or second order kinetics. The first order model is again the more likely case but a discussion of a potential second order model will be reviewed in the section titled Comparison to Theoretical Models.

The average TOC first order reaction rate constant is -0.0153/day. The rate constants listed in Table 2.7 are generally one magnitude higher than determined from the the TOC data for the experimental piles. The TOC data for this study includes the organic carbon content of the biomass. This may explain the differences in the magnitude of the rate constants. The measured TOC value is higher than the actual TOC of just the substrate. If the biomass TOC content was subtracted from the experimental measured value,.the actual decomposition rate could of been determined.

In comparing the first order rate constants for the % C and TOC parameters, the average pile TOC rate constant is over 10 times higher than the average pile rate constant for % C. This higher rate constant value is expected because the TOC parameter measures the readily available water soluble organic carbon content. The measured % C content includes the organic carbon content of all constituents including the more resistant compounds cellulose, hemicellulose and lignin. Paul and Clark (1989) outline the rate constants for plant residues in soils under laboratory conditions. They indicate for easily decomposable compounds $-k = 0.2$ compared to $-k = 0.08$ for slowly decomposable constituents. The

multicomponent empirical models proposed by Murayama *et al.* (1990) and Van Veen *et al.* (1984) support the argument that different fractions of plant residues decompose at different rates. The reaction rate of the easily decomposable fraction is higher than the more resistant fraction of the plant residue. The following section compares the decomposition modelling results with the theoretical physical model proposed by Haug (1980).

4.2.2 Comparison to Theoretical Model

The modelling results for the parameters % C and TOC over time indicated the the decomposition of the organic materials followed either first or second order kinetics. Generally, the decomposition of organic material is considered to follow first order kinetics Haug (1980), (Paul and Clark 1989). The following section reviews the model proposed by Haug (1980) and discusses the model in relation to experimental decomposition rates and changes in compost substrate and biomass. The composting kinetic model proposed by Haug (1980) is shown below.

$$-\frac{ds}{dt} = \frac{k A_v X}{K_x + X} \qquad (25)$$

-ds/dt = rate of hydrolysis of solid substrate

k = maximum rate of hydrolysis occurring at high microbial population.

A_v = Available surface area (substrate) per unit volume

K_x = half velocity coefficient The microbial concentration at 1/2 the maximum reaction rate.

Haug (1993) indicated that the solubilization of the solid substrate through hydrolysis is probably the rate limiting mechanism during composting. Based on his model, the rate of hydrolysis is a function of the size of the microbial population **X**, and the available substrate surface area per unit volume A_v. Haug (1980) described two general cases of the model. Case 1 when the

concentration of microbes is much less than K_x (the half-rate constant) the rate of hydrolysis of the solid substrate is a first order reaction with respect to the microbial concentration. Case 2 when the concentration of microbes is much greater than the half rate constant the change in solid substrate over time is a zero order reaction with respect to microbial concentration.

Haug (1980) noted that different decomposition rates observed for different substrate materials are probably due to differences in the value of kA_V. For example, a more resistant substrate such as wood fiber would have a lower value of kA_V. Haug (1980) suggested this may be interpreted as a lower number of available enzyme binding sites or a lower number of successful enzyme reactions in a more resistant substrate. The product kA_V appears to be a measure of substrate availability and the value changes throughout the composting process. Haug (1993) indicated that during the early stages of composting, the substrates with high kA_V values (kA_{V1}) are decomposing resulting in an increase in microbial population. As the composting process proceeds, the more resistant substrates with low kA_V values (kA_{V2}) are encountered. The rate of hydrolysis of the more complex substrates are the rate determining step of the overall process. The more recalcitrant substrates decompose at lower rates for a longer period of time (Haug 1993; Marugg *et al.* 1993). The changes in % C in solid samples and TOC in water extracts over time provided evidence that the decomposition rate is higher during the active phase and lower during the maturation phase based on the change in slope of the curves. Haug (1993) also suggested the values of K_x are likely a function of the type of substrate and should increase as the number of active sites per unit volume increases. Based on this suggestion, the values of K_x would also change as the compost substrate changes.

In addition to changes in substrate, the concentration and the types of microorganisms also change during the composting process. During the early mesophilic stage, when the more easily available substrates are consumed, the microbial population especially bacteria increases exponentially (Biddlestone *et al.* 1987). As the temperature increases above 40^0C the mesophilic organisms die off

and the thermophilic organisms flourish. During the thermophilic stage, the compost pile temperature continues to increase to above 60^0C (Biddlestone *et al.* 1987). Above 60^0C, microbial activity decreases significantly as the fungi are deactivated, and spore-forming bacteria and actinomycetes prevail. The microbial concentration or biomass during the early stages of composting (mainly bacteria) will be represented by the term X_1. After the peak temperature period is reached, the compost mass enters a cooling stage marked by a decrease in compost pile temperature and represents a decrease in available substrate. During the cooling stage, fungi and actinomycetes attack the more resistant hemicellulose and cellulose fractions breaking them down to simple sugars which may be used by variety of microorganisms (Biddlestone *et al.* 1987). The biomass concentration in the maturation phase of composting when fungi and actinomycetes dominate will be represented by the term X_2.

In the later stages of composting a mixture of solid waste and sewage sludge, de Bertoldi *et al.* (1983) observed a continuous decrease in the number of cellulolytic bacteria to about 10^2 per gram dry weight (50 days). The maximum cellulolytic bacteria count was between 10^3 to 10^4 per gram dry weight, after about 25 days of composting. de Bertoldi *et al.* (1983) indicated the number of cellulolytic fungi increased to approximately 10^8 per gram dry weight in the later stages of composting (50 days) The cellulolytic fungi count was approximately 10^5 per gram dry weight at the start of the composting process. The number of actinomycetes also increased to between 10^6 to 10^7 per gram dry weight in the later stages of the composting process from the initial.count of approximately 10^4 per gram dry weight (de Bertoldi *et al.* 1983). The compost pile temperature continues to drop to ambient conditions due to lower microbial activity and decomposition rate. Although the concentrations of fungi and actinomycetes increased in the later stages of composting, the overall biomass concentration is expected to decrease, due to a reduction in available substrate. None of referenced composting literature sources specifically noted the fact the concentration of biomass decreased during the maturation phase.

Table 4.15 summarizes the relative values for the various terms in Haug's model for both the active and maturation phases of the composting process.

Table 4.15 - Composting Model Conditions

Term	Active Phase	Maturation Phase
k	High	Low
S	High S	Low S
A_V	High A_{V1}	High A_{V2} Low A_{V1}
X	High X_1 Low X_2	High X_2 Low X_1
Model Case		
$X << K_x$	$\frac{ds}{dt} = \frac{k A_V X}{K_x}$	$\frac{ds}{dt} = \frac{k A_V X}{K_x}$
$X >> K_x$	$\frac{ds}{dt} = k A_V$	$\frac{ds}{dt} = k A_V$

Based on this discussion of Haug's model and its parameters, it appears the rate of hydrolysis, A_V, biomass concentration and type, K_X and the kinetic rate vary throughout the different stages of the process. The two general model cases apply to both the active and maturation stage. Haug's proposed model provides valuable insight into the composting process, but it looks mainly at biomass concentration and does not deal with the relationship between the biomass concentration and the available substrate. The biomass concentration **X** is a function of the available substrate through the the yield coefficient **Y**. The yield coefficient is defined as the ratio of mass of cells formed to the mass of substrate consumed (Metcalf

and Eddy, Inc. 1991). Haug (1980) stated the term A_V is likely related to the total number of enzyme absorption sites on the substrate. Therefore, the available substrate concentration is a function of the available surface area per volume (A_V). With respect to substrate, the two general cases are reviewed below.

Case 1 when the concentration of microbes is much less than K_X (the half-rate constant) the rate of hydrolysis of the solid substrate is a second order reaction with respect to A_V (related to substrate concentration) and X which is a function of the substrate concentration through the yield coeffficient. Case 2 when the concentration of microbes is much greater than the half rate constant the change in solid substrate over time is a first order reaction with respect A_V.

In summary, the kinetic rates determined for the various experimental compost piles indicated the overall decomposition rate during the active phase may be either first or second order.with respect to substrate concentration. A possible explanation for the second order results is the rate of hydrolysis of the substrate may depend upon A_V (related to substrate concentration) and microbial concentration X which is a function of the available substrate concentration through the yield coefficient. A second possible explanation is the measured % C and TOC values included the carbon content of both substrate and the biomass.

Future research opportunities include determining values for the various kinetic model variables and testing the kinetic model.

4.2.3 Comparison of Individual Piles

The first order decomposition rates for the various piles are generally quite similar and only a few piles are deemed to be significantly different. Multiple t tests were performed to determine which piles were significantly different based on the first order decomposition rate constants (k). The statistical results are summarized in Tables F.2 and F.3 in Appendix F. Table 4.16 outlines the piles that are significantly different for the % C data.

Table 4.16 - Piles found to be Significantly Different - % C data

1st Order k values for % C data

Rank by k value	Pile No.	Pile Designations	Piles Significantly different
1(Highest)	8	Hi C:N, Hi M.C., Hi Por.	Piles 5, L1, L3, L4
2	L 2	Low C:N, Low M.C., Low Por.	Piles L1, L3, L4
3	4	Hi C:N, Hi M.C., Low Por.	
4	3	Med C:N, Hi M.C., Low Por.	
5	R 2	Med C:N, Hi M.C., Hi Por.	
6	6	Hi C:N, Low M.C., Hi Por.	
7	7	Med C:N, Hi M.C., Hi Por.	
8	1	Med C:N, Low M.C., Low Por.	
9	R 1	Med C:N, Hi M.C., Hi Por.	
10	5	Med C:N, Low M.C., Hi Por.	Pile 8
11	L 4	Low C:N, Low M.C., Hi Por.	Piles 8, L2
12	L 3	Low C:N, Hi M.C., Hi Por.	Piles 8, L2
13	L 1	Low C:N, Hi M.C., Low Por.	Piles 2, 8, L2
14 (Lowest)	2	Hi C:N, Low M.C., Low Por.	Pile L1

Piles 8 and L2 had the largest decomposition k values and were found to be significantly different than the low C:N ratio piles L1, L3, and L4. Pile 8 was also different than Pile 5. Pile 2 a high C:N ratio, low moisture content pile had the lowest decomposition rate and was found to be significantly different than pile L1. There appears to be no consistent reasoning, based on the experimental levels of the operating variables, to explain the ranking order and significant differences between the decomposition rates of the piles. The decomposition rates for the high C:N ratio, high moisture content piles 8 and 4 were expected to be high in comparison to the other piles. However, Pile L2 a low C:N ratio, high moisture content pile was not expected to have the second largest decomposition rate. Pile L3 the other low C:N ratio, high moisture content pile was ranked 12 overall. The decomposition rates for the low C:N ratio piles except for Pile L2 were generally low in the rankings. Table 4.17 outlines the piles that are significantly different for the TOC data.

Table 4.17 - Piles Significantly Different - TOC data

1st Order k values for TOC data

Rank by k value	Pile No.	Pile Designations	Piles Significantly different
1(Highest)	3	Med C:N, Hi M.C., Low Por.	Pile L4
2	8	Hi C:N, Hi M.C., Hi Por.	Pile L4
3	7	Med C:N, Hi M.C., Hi Por.	Pile L4
4	2	Hi C:N, Low M.C., Low Por.	
5	R 1	Med C:N, Hi M.C., Hi Por.	
6	L 1	Low C:N, Hi M.C., Low Por.	
7	L 2	Low C:N, Low M.C., Low Por.	
8	R 2	Med C:N, Hi M.C., Hi Por.	
9	4	Hi C:N, Hi M.C., Low Por.	
10	5	Med C:N, Low M.C., Hi Por.	
11	1	Med C:N, Low M.C., Low Por.	
12	L 3	Low C:N, Hi M.C., Hi Por.	
13	6	Hi C:N, Low M.C., Hi Por.	
14 (Lowest)	L 4	Low C:N, Low M.C., Hi Por.	

Piles 3, 8 and 7 had the largest 1st order decomposition k values and were found to be significantly different than L4 which had the lowest value. Again there appears to be no consistent reasoning, based on the experimental levels of the operating variables, to explain the ranking order and significant differences between the decomposition rates of the piles. The maturity parameter $C:N_W$ cannot be used to indicate which piles matured first as none of the values were between the range of 5 to 6. Possible reasons for the differences observed between the experimental and literature values are sample preparation techniques, testing errors, possible sample contamination, and different organic materials.

4.2.4 Summary and Explanations

In summary, the decomposition rates for the parameters % C and TOC over time were found to follow either first or second order kinetics. Based on ANOVA tests there were no differences between the average pile R^2 values for the first and second order kinetic models. Generally the decomposition of organic materials is considered to follow first order kinetics. The first order decomposition rate constants for both parameters were lower than literature values.

A possible explanation for the second order results is the rate of hydrolysis of the substrate may depend upon A_V and microbial concentration **X** which is a function of the available substrate concentration through the yield coefficient

Finally the first order decomposition rates for the various piles were compared using an ANOVA. Although there were some significant differences between some of the piles, there was no consistent reasoning based on the experimental levels to explain the results. The ranking of the piles by first order decomposition rate constants, therefore, cannot be used to verify which operational parameters influenced the rate of decomposition. Possible reasons for these experimental results are: inadequate material mixing, actual C:N ratio levels, sampling and testing errors and the difficulties experienced in trying to control moisture content of the piles.

4.3 Temperature and % Oxygen Results

Compost pile temperatures were measured to: **1**. identify the different stages of the composting process; **2**. provide an indication of process performance; **3**. to evaluate the the effectiveness of rebuilding the compost piles; **4**. serve as a secondary indicator of compost maturity. The following sections discuss the trends in compost pile temperatures and % oxygen readings and the results of the ARIMA (Autoregressive integrated moving average) analysis.

4.3.1 Trends in Pile Temperature and % Oxygen Readings

The average pile temperature for the various piles generally followed a decreasing trend throughout the first 65 days of the process and then increased to over 60^{0}C after the piles are rebuilt and covered with burlap and mature compost. The initial average temperatures for the compost piles were approximately 65^{0}C. No mesophilic stage was observed. Based on the fact the yard waste was picked up from the different areas of the city on a weekly basis it is highly possible the degradation process had already started prior to the development of the windrows. The peak thermophilic stage for most of the piles was approximately 16-20 days in length. After this period, the average pile temperatures generally followed a decreasing trend until the piles were rebuilt and covered. The average pile temperatures prior to rebuilding ranged from 28.9^{0}C for pile 1 to 54.3^{0}C for pile 7. Most of the piles had an average temperature of approximately 30^{0}C with mean ambient temperatures in the 3 to 8^{0}C range. The cooling stage is generally characterized as the period, when the compost pile temperature decreases to ambient conditions due to lower microbial activity (Biddlestone *et al.* 1987). The compost piles were rebuilt prior to the conclusion of the initial cooling stage. As indicated, after the compost piles were rebuilt the average pile temperature increased to over 60^{0}C and stayed above 50^{0}C for most of November 1992 when the mean ambient temperatures were in the range of -2 to 2^{0}C. The pile temperatures then gradually decreased to ambient temperatures after approximately 180 days signalling the start of the maturation stage. The average pile temperature serves as a secondary and approximate indicator of maturity. Figures D.1 to D.16 show changes in the average pile temperatures for the various piles. Table D.1 in Appendix D summarizes the average monthly pile temperatures. The average monthly temperatures for most of the piles were close in value except for piles 3, 6 and 8 during the November 1992 to January 1993 time frame. Control piles C1 and C2 generally had higher average monthly temperatures in September and October of 1992 than most of the experimental piles. The most likely explanation for these higher temperatures is the control piles were

not as far along as the experimental piles in the composting process. Conversely the average monthly temperatures for the control piles were lower during December and January. The differences are probably due to the installation of the passive aeration system, rebuilding and covering of the experimental piles.

The % oxygen content of the various piles fluctuated for the first 130-140 days and then levelled off at values close to ambient conditions. Figures D.17 to D.32 show changes in the average % oxygen readings for the various piles. The oxygen readings ranged from values of 10 to 20.9%. which are much higher than the minimum value of 5%. The method of measurement may have introduced oxygen into the pile resulting in a higher readings. The next section discusses the results of the time series ARIMA analyses for compost pile temperature data.

4.3.2 Arima Analyses - Results

Arima (Autoregressive integrated moving average) analysis was used to investigate the influence interventions such as turning, watering, rebuilding and adding additional wood chips to the experimental piles had on the average pile temperatures over the composting period. The main purpose of these interventions were to try to maintain the experimental levels of the operational variables for the factorial experiments. For example, the piles were watered to try to increase the moisture content to the desired levels. Usually the piles were mechanically turned the same day to homogenize the compost materials therefore more than one intervention was carried on the same day or prior to the next temperature reading. This experiment was not specifically designed to evaluate the various interventions using Arima analysis therefore the results must be fairly consistent in order to support any conclusions. Installing the passive aeration system, rebuilding and covering the experimental piles was the only intervention that was not directly connected to maintaining the experimental levels.

Arima models are used to mathematically describe the random disturbances in a time series. These models can involve the use of three different processes namely autoregression, differencing

(integration) and moving averages. Not all models involve the use of all three processes. For example, the appropriate model for the compost temperature time series was an Arima (1,0,0) model. The usual nomenclature defining an Arima model is Arima (p,d,q). The p defines the order of autoregression, d the degree of differencing and q the order of moving average. The Arima (1,0,0) model is a first order autoregressive process and does not involve differencing and moving average processes. In the autoregression process, each value in a time series is a function of one or more preceding values. The equation shown below defines the relationship for a first order autoregressive process (SPSS for Windows Trends Manual 1993).

$$\text{Value}_t = \text{disturbance}_t + \text{ARI coefficient} * \text{Value}_{t-1} \quad (29)$$

ARI coefficient = autoregressive coefficient

The value of the ARI coefficient indicates how strongly the value at time t is dependent on the preceding value (1993). ARI coefficient values close to 1 as calculated in these analyses indicates there is a strong relationship between the series value at time t and the preceding value. The model coefficients for the various interactions are listed in Table 4.18. A negative value indicates the pile temperature increased as a result of the intervention. Based on 95% probability the coefficients highlighted in bold were considered significant.

Table 4.18 - ARIMA Analyses - Results
Variable- Average Pile temperatures

Pile	AR1	Mixing	Watering	Rebuild	Porosity
Pile 1	**0.9695**	0.785	**-7.586**	**-14.850**	
Pile 2	**0.9186**	-1.861	-0.270	-9.990	
Pile 3	**0.9227**	-1.323	3.322	**-12.788**	
Pile 4	**0.9459**	-0.114	-3.718	**-12.298**	
Pile 5	**0.9127**	-1.668	1.691	-9.986	-8.696
Pile 6	**0.9635**	0.789	**-7.467**	**-14.751**	-0.440
Pile 7	**0.9801**	2.661	**-5.418**	1.152	**9.669**
Pile 8	**0.9274**	-0.652	-2.203	5.019	-5.430
Pile R1	**0.9705**	1.101	1.700	**-13.200**	**-10.705**
Pile R2	**0.9724**	2.189	1.619	-6.551	1.494
Pile L1	**0.9721**	-3.304	**-4.730**	-5.802	
Pile L2	**0.9456**	-4.818	0.447	0.114	

Based on the model coefficient values the mixing, watering and porosity adjustment interventions did not consistently influence the average pile temperatures. For example, seven piles with negative model coefficients indicated mixing increased the temperature. Five piles with positive values suggested mixing decreased the average pile temperature. Five piles had significant negative model coefficients for the intervention pile rebuilding. These results support the conclusion that the installation of a passive aeration system, and the rebuilding and covering of the compost piles resulted in higher compost temperatures. The average pile temperature after the intervention was higher than the temperature before the intervention.

5.0 SUMMARY AND CONCLUSIONS

The objectives of this study were to **1)** systematically evaluate the influence of key operational parameters on the decomposition rate of yard waste and **2)** identify a practical indicator of compost stability and maturity. A factorial experiment was selected to evaluate the influence of the operational variables, because it is the most efficient method to estimate the effects of two or more factors and the their interactions. The factorial results using the % decrease in the TOC as the response variable found none of the effects to be significant at the 5% significance level. The 90% confidence intervals, half normal plots and effect rankings for the full composting period provided indications the 13, (C:N ratio-Porosity) 23 (MC-Porosity) and the 123 (C:N ratio-MC-Porosity) interactions marginally influenced the decomposition rate of the organic materials. Generally, the results do not support the hypotheses that the operating variables C:N ratio, moisture content and porosity adjustment individually affected the decomposition rate of the organic materials. Possible explanations for these experimental results are: 1) the response variables used in the study were not able to measure the effects , 2) the effect of C:N ratio, M.C. and porosity on degradation did not occur within the ranges tested or 3) the difficulties encountered in maintaining and operating a field level experiment impacted the results. The most likely reasons are the difficulties in maintaining and operating a field level experiment. For example, the difficulty experienced trying to maintain the experimental moisture levels may have effected the factorial results. It was not possible to maintain the moisture content of the pile sections at the desired levels.

The purpose of monitoring the decomposition of the organic materials for the various compost piles was to: **1)** evaluate and model the biological degradation of these materials over time and provide a tool for optimization of the process, **2)** determine the magnitude and rate of decomposition of the various compost piles and compare the results with expected behavior. The decomposition rates for the parameters % C and TOC over time were found to follow either first or second order kinetics with respect to substrate

concentration. A possible explanation for the second order results is the rate of hydrolysis of the substrate may depend upon A_V (related to substrate concentration) and microbial concentration which is a function of the available substrate concentration through the yield coefficient. A second explanation is the % C and TOC data included both the carbon content of substrate and biomass. The data does not represent the change in just substrate carbon over time. The first order decomposition rates for the various piles were compared using multiple t tests. Although there were some significant differences between some of the piles, there was no consistent reasoning based on the experimental levels to explain the results. The ranking of the piles by first order decomposition rate constants, therefore, cannot be used to verify which operational parameters influenced the decomposition rate.

An Arima analysis of the average pile temperature data indicated the average pile temperature increased as a result of rebuilding, covering and installing a passive aeration system. The average monthly temperatures for the control piles were lower during December and January than the rebuilt experimental piles. The results support the hypothesis that building up the compost piles will result in higher pile temperatures during the cooler ambient conditions. The degradation of the organic materials; therefore, is not greatly reduced by the cold ambient temperatures. By retaining enough heat, higher compost temperatures are maintained which promotes the continued optimal decomposition of the organic materials.

The second objective of this study was to identify a practical indicator of compost stability and maturity. The final $C:N_W$ ratio values for the experimental piles did not fall between the range of 5 to 6 indicated by others as the absolute indication of maturity. The OUR parameter was dropped from the experimental plan, after several attempts to solve the problem of leaks in the tubing were not successful. The change in % C and TOC over time provided some indication, when the active composting period had ended and the maturation stage had started. At this point, there is a definite change in the slope of the curve for the various piles. Finally, the

average pile temperatures gradually decreased to ambient temperatures after approximately 180 days signalling the start of the maturation stage. In summary, no parameter used in this study was identified as a absolute indicator of compost maturity.

Suggestions to improve future research efforts include grinding up the straw prior to mixing, weighting the mass of each organic material, and developing more replicate piles. In addition, the use of the D.O. oxygen meter to measure the OUR rates of the compost should be investigated and evaluated. It is critical to establish more than one reliable response variable to verify the experimental results.

Future areas of research may include determining values for the terms k, A_v, X and K_X for Haug's kinetic model and testing the model with respect to substrate concentration.

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7.0 APPENDICES

Appendix A - Solid Sample Parameter Data

Table A.1- Solid Sample Parameter Data

Pile 1

Sample Date	Days	%MC	Avg % VS	S	Avg % C	% N	Avg C:N ratio
92-08-02	3	59.54	65.20	5.09	36.22	2.12	17.12
92-08-11	12	36.74	55.39	5.76	30.77	1.85	16.59
92-08-16	17	41.56	19.50	19.50	33.88	1.92	17.66
92-08-23	24	29.27	57.45	3.45	31.92	2.59	12.34
92-09-02	34	30.05	77.57	22.38	43.09	1.52	28.40
92-09-13	45	48.12	41.47	3.06	23.04	1.99	11.56
92-09-26	58	43.24	47.66	6.73	26.48	2.20	12.04
92-10-20	82	46.22	37.09	3.24	20.60	2.07	9.94
92-11-19	112	36.97	33.73	0.91	18.74	1.85	10.15
93-01-12	165	39.42	36.22	0.23	20.12	1.74	11.58
93-03-13	225	18.71	36.05	0.47	20.03	2.06	9.72

Pile 2

Sample Date	Days	%MC	Avg % VS	S	Avg % C	% N	Avg C:N ratio
92-08-02	2	38.63	41.84	2.31	23.24	2.28	10.19
92-08-11	11	19.96	47.90	17.39	26.61	1.54	17.29
92-08-16	16	18.96	60.99	1.56	33.88	1.65	20.56
92-08-23	23	15.97	66.09	7.54	36.72	1.47	25.04
92-09-04	35	28.84	43.91	12.49	24.39	1.62	15.02
92-09-13	44	29.28	48.32	6.90	26.85	1.28	20.93
92-09-26	57	30.68	34.81	10.31	19.34	1.10	17.65
92-11-05	97	25.22	21.45	0.43	11.92	1.03	11.59
92-11-19	111	22.88	21.99	0.92	12.21	1.01	12.06
93-01-12	164	34.90	22.83	0.92	12.68	1.28	9.91
93-03-13	224	23.29	23.96	0.87	13.31	0.99	13.49

Multiple Sample Data

Sample Date	Position	% MC	Avg % VS	S	Avg % C
92-09-26	X	51.11	40.91	5.49	22.73
	Y	33.30	54.60	3.13	30.33
	Z	45.32	47.47	4.79	26.37
	Pile Avg	**43.24**	**47.66**		**26.48**
	S	9.09			
92-10-20	X	47.38	36.20	2.78	20.11
	Y	43.02	37.47	4.93	20.81
	Z	48.27	37.59	2.87	20.88
	Pile Avg	46.22	37.09		20.60
	S	2.81			
92-09-26	X	27.72	44.63	13.04	24.79
	Y	33.68	29.32	6.08	16.29
	Z	30.64	30.49	0.45	16.94
	Pile Avg	30.68	34.81		19.34
	S	2.98			

Pile 3

Sample Date	Days	% MC	Avg % VS	S	Avg % C	% N	Avg C:N ratio
92-08-02	2	49.51	60.17	10.69	33.43	2.55	13.12
92-08-11	11	18.02	71.10	9.77	39.50	1.43	27.53
92-08-16	16	31.13	64.75	0.90	35.97	1.99	18.06
92-08-26	26	51.26	66.35	6.54	36.86	1.36	27.02
92-09-04	35	36.66	75.53	2.77	41.96	1.81	23.21
92-09-13	44	32.09	51.71	4.76	28.73	1.71	16.85
92-09-28	59	48.09	33.56	4.78	18.65	1.37	13.58
92-10-18	79	43.69	38.86	6.05	21.59	1.33	16.26
92-11-19	111	45.63	32.04	0.94	17.80	1.91	9.34
92-01-14	166	43.72	25.40	0.23	14.11	0.94	15.04
92-03-13	224	43.41	27.38	0.13	15.21	1.36	11.19

Multiple Sample Data

Sample Date	Position	% MC	Avg % VS	S	Avg % C
92-09-28	X	47.45	33.29	0.25	18.49
	Y	46.03	28.90	1.03	16.05
	Z	50.80	38.51	3.10	21.39
	Pile Avg	48.09	33.56		18.65
	S	2.45			
92-10-18	X	44.60	32.46	6.21	18.04
	Y	41.71	41.83	5.68	23.24
	Z	44.76	42.29	1.25	23.49
	Pile Avg	43.69	38.86		21.59
	S	1.71			

Pile 4

Sample Date	Days	% MC	Avg % VS	S	Avg % C	% N	Avg C:N ratio
92-08-03	4	58.55	60.21	19.38	33.45	1.67	20.08
92-08-06	7	35.08	78.96	4.12	43.86	2.11	20.77
92-08-11	12	42.86	72.14	19.50	40.08	2.17	18.50
92-08-16	17	39.98	66.79	6.73	37.11	2.07	17.92
92-08-23	24	34.90	61.06	2.92	34.54	1.93	17.86
92-09-02	34	58.29	49.68	12.29	27.60	1.85	14.92
92-09-13	45	49.71	42.63	4.83	23.68	1.46	16.23
92-09-26	58	52.38	39.22	7.43	21.79	1.70	12.80
92-10-15	77	50.15	33.55	5.71	19.19	1.60	12.01
92-11-19	112	39.32	29.71	1.79	16.51	1.50	11.00
93-01-12	165	44.27	29.04	0.14	16.13	1.49	10.81
93-03-13	225	29.30	28.53	0.25	15.85	1.59	9.99

Sample Date	Position	% MC	Avg % VS	S	Avg % C
92-09-26	X	54.08	37.58	6.46	20.88
	Y	52.91	45.55	8.72	25.31
	Z	50.15	34.54	2.42	19.19
	Pile Avg	52.38	39.22		21.79
	S	2.02			
92-10-15	X	48.88	29.05	2.42	16.14
	Y	50.98	34.42	8.68	19.12
	Y'	51.86	36.41	7.22	20.23
	Z	48.78	34.34	0.95	19.08
	Pile Avg	50.12	33.55		18.64
	S	1.54			

Pile 5

Sample Date	Days	% MC	Avg % VS	S	Avg % C	% N	Avg C:N ratio
92-08-02	2	58.43	57.46	16.16	31.92	2.43	13.13
92-08-11	11	29.23	47.50	15.79	26.39	1.65	16.04
92-08-16	16	36.79	64.05	2.82	35.58	1.91	18.60
92-08-23	23	51.43	62.31	8.56	34.62	1.69	20.43
92-09-04	35	45.46	48.61	6.39	27.01	1.40	19.30
92-09-13	44	30.21	58.82	0.38	32.68	1.69	19.29
92-09-28	59	44.31	36.47	5.68	20.26	1.88	10.77
92-10-18	79	42.97	43.45	4.15	24.14	1.60	15.04
92-11-19	111	32.05	31.06	2.63	17.26	1.59	10.84
93-01-14	166	37.54	28.80	0.30	16.00	1.50	10.67
93-03-13	224	17.70	29.02	0.80	16.12	1.45	11.11

Multiple Sample Data

Sample Date	Position	% MC	Avg % VS	S	Avg % C
92-09-28	X	47.60	41.85	1.84	23.25
	Y	43.09	33.97	7.56	18.87
	Z	42.25	33.58	4.37	18.65
	Pile Avg	44.31	36.47		20.26
	S	2.88			
92-10-18	X	30.06	41.02	1.00	22.79
	Y	49.86	44.47	4.25	24.70
	Z	48.98	44.86	2.45	24.92
	Pile Avg	42.97	43.45		24.14
	S	11.18			

Pile 6

Sample Date	Days	% MC	Avg % VS	S	Avg % C	% N	Avg C:N ratio
92-08-03	4	45.70	80.20	2.71	44.56	1.73	25.80
92-08-06	7	39.67	78.35	1.00	43.53	2.14	20.35
92-08-11	12	27.42	85.04	7.51	47.24	2.17	21.74
92-08-16	17	29.46	60.44	6.92	33.58	1.71	19.66
92-08-23	24	29.11	60.33	3.97	33.52	1.85	18.15
92-09-02	34	33.02	54.36	5.68	30.20	1.80	16.74
92-09-13	45	42.53	46.18	0.55	25.66	1.62	15.85
92-09-26	58	41.20	52.73	4.29	29.30	2.01	14.58
92-10-15	77	45.44	48.34	9.65	26.86	1.67	16.05
92-11-19	112	29.42	35.36	4.69	19.65	1.79	10.99
93-01-12	165	23.63	35.41	1.67	19.67	1.85	10.62
93-03-13	225	27.27	35.74	1.64	19.86	1.58	12.57

Multiple Sample Data

Sample Date	Position	% MC	Avg % VS	S	Avg % C
92-09-26	X	39.33	49.82	4.64	27.68
	Y	39.94	52.33	2.84	29.07
	Z	44.32	56.04	4.89	31.13
	Pile Avg	41.20	52.73		29.30
	S	2.72			
92-10-15	X	54.52	52.57	2.81	29.21
	Y	46.55	54.54	5.50	30.30
	Y'	37.02	44.52	18.28	24.73
	Z	43.69	41.74	3.75	23.19
	Pile Avg	45.44	48.34		26.86
	S	4.89			

Pile 7

Sample Date	Days	% MC	Avg % VS	S	Avg % C	% N	Avg C:N ratio
92-08-02	3	55.83	73.01	1.81	40.56	2.91	13.92
92-08-06	7	56.24	63.60	22.42	35.33	2.08	17.02
92-08-11	12	45.59	59.17	9.77	32.87	2.11	15.59
92-08-16	17	37.94	59.84	8.27	33.24	2.14	15.54
92-08-23	24	34.24	61.63	2.37	34.24	1.70	20.15
92-09-02	34	49.94	52.99	4.87	29.44	1.96	14.99
92-09-13	45	44.38	47.72	2.18	26.51	1.56	17.04
92-09-26	58	52.07	35.87	4.27	19.93	1.74	11.45
92-10-15	77	54.32	32.54	12.82	20.26	1.46	13.91
92-11-19	112	41.68	35.48	2.52	19.71	1.46	13.53
93-01-12	165	42.76	36.40	0.83	20.22	1.53	13.25
93-03-13	225	25.88	32.06	0.62	17.81	1.69	10.52

Pile 8

Sample Date	Days	% MC	Avg % VS	S	Avg % C	% N	Avg C:N ratio
92-08-02	2	58.64	60.21	19.38	33.45	1.55	21.60
92-08-11	11	39.76	61.30	4.06	34.06	1.34	25.50
92-08-16	16	29.25	58.78	9.35	32.66	1.36	24.03
92-08-23	23	29.07	62.76	6.82	39.24	1.73	22.63
92-09-04	35	37.34	60.53	7.26	33.63	2.10	16.04
92-09-13	44	40.16	45.80	2.47	25.44	1.24	20.55
92-09-28	59	44.48	32.60	8.42	19.00	1.12	16.96
92-10-18	79	40.98	36.16	6.47	20.39	1.11	18.29
92-11-19	111	35.44	20.56	2.04	11.42	0.91	12.58
93-01-12	164	31.73	24.16	2.45	13.63	1.29	10.56
93-03-13	224	24.67	15.98	14.35	8.88	1.05	8.46

Multiple Sample Data

Sample Date	Position	% MC	Avg % VS	S	Avg % C
92-09-26	X	47.77	34.74	1.67	19.30
	Y	56.07	40.82	3.15	22.68
	Z	52.37	32.05	2.95	17.81
	Pile Avg	52.07	35.87		19.93
	S	4.16			
	X	54.03	20.77	23.49	11.54
	Y	58.84	38.28	1.89	21.26
	Y'	52.50	33.25	6.49	18.47
	Z	51.63	37.88	2.43	21.04
	Pile Avg	54.32	32.54		20.26
	S	3.22			
92-09-28	X	41.03	23.94	1.01	13.30
	Y	44.08	33.04	7.79	20.85
	Z	48.32	40.80	6.61	22.84
	Pile Avg	44.48	32.60		19.00
	S	3.66			
92-10-18	X	44.07	33.73	7.12	18.74
	Y	40.86	40.26	5.63	21.00
	Z	38.01	34.50	8.24	21.43
	Pile Avg	40.98	36.16		20.39
	S	3.03			

Pile R1

Sample Date	Days	% MC	Avg % VS	S	Avg % C	% N	Avg C:N ratio
92-08-02	3	62.13	52.44	6.35	29.13	2.54	11.45
92-08-06	7	46.28	67.76	5.43	37.64	2.56	14.72
92-08-11	12	40.14	69.89	3.21	38.83	2.78	13.99
92-08-16	17	43.62	58.89	12.35	32.72	2.56	12.79
92-08-23	24	45.81	71.69	9.78	39.83	2.42	16.47
92-09-05	37	48.37	59.71	1.80	33.17	1.74	19.04
92-09-13	45	50.75	42.88	1.28	23.82	2.11	11.29
92-09-28	60	58.79	42.26	3.53	23.48	0.80	29.26
92-10-20	82	49.52	43.74	2.67	24.30	1.37	17.77
92-11-19	112	43.56	33.04	4.49	18.36	2.02	9.11
93-01-12	165	43.09	33.05	0.56	18.36	1.77	10.35
93-03-13	225	23.89	43.13	0.94	23.96	1.58	15.15

Multiple Sample Data

Sample Date	Position	% MC	Avg % VS	S	Avg % C
92-10-20	X	44.07	43.01	1.81	23.90
	Y	52.45	41.95	2.47	23.31
	Z	52.02	46.24	2.76	25.69
	Pile Avg	49.52	43.74		24.30
	S	4.72			

Pile R2

Sample Date	Days	% MC	Avg % VS	S	Avg % C	% N	Avg C:N ratio
92-08-02	3	58.41	63.07	1.66	35.04	2.87	12.20
92-08-06	7	53.17	54.18	36.55	30.10	2.14	14.10
92-08-11	12	35.06	78.57	15.39	43.65	3.10	14.08
92-08-16	17	51.64	64.43	2.79	35.80	2.89	12.39
92-08-23	24	45.81	51.81	29.01	28.78	2.41	11.93
92-09-05	37	39.78	50.58	1.40	28.10	1.74	16.13
92-09-13	45	50.14	53.39	0.42	29.66	2.24	13.25
92-09-28	60	44.72	29.75	2.76	16.53	1.87	8.86
92-10-20	82	47.30	36.69	5.75	20.39	1.17	17.38
92-11-19	112	37.96	30.09	2.34	16.72	1.80	9.31
93-01-14	167	38.03	30.79	0.16	17.11	1.86	9.20
93-03-13	225	41.09	27.05	0.18	15.03	1.55	9.68

Multiple Sample Data

Sample Date	Position	% MC	Avg % VS	S	Avg % C
92-10-20	X	52.92	44.07	3.03	24.48
	Y	41.88	32.32	1.36	17.95
	Z	47.09	33.70	3.72	18.72
	Pile Avg	47.30	36.69		20.39
	S	5.52			

Pile L1

Sample Date	Days	% MC	Avg % VS	S	Avg % C	% N	Avg C:N ratio
92-08-02	3	59.36	47.74	0.50	26.52	2.22	11.93
92-08-06	7	48.51	44.94	18.24	24.97	2.20	11.36
92-08-16	17	39.51	37.43	4.24	20.79	1.97	10.54
92-08-27	28	52.52	50.60	13.00	28.11	1.96	14.32
92-09-05	37	54.64	42.95	5.22	23.86	1.66	14.34
92-09-13	45	53.98	51.01	1.40	28.34	1.83	15.48
92-09-28	60	54.11	33.67	3.79	18.71	1.96	9.56
92-10-20	82	52.59	35.83	1.45	19.90	1.48	13.41
92-11-21	114	45.28	26.05	2.41	14.47	1.55	9.32
93-01-14	167	40.02	28.48	0.36	15.82	1.45	10.91
93-03-13	225	17.59	29.67	0.04	16.49	1.59	10.36

Pile L2

Sample Date	Days	% MC	Avg % VS	S	Avg % C	% N	Avg C:N ratio
92-08-02	3	59.53	73.64	9.39	40.91	2.40	17.03
92-08-06	7	63.97	57.77	21.42	32.10	2.53	12.67
92-08-16	17	39.59	42.21	4.24	23.45	1.79	13.09
92-08-27	28	43.30	69.34	3.36	38.52	1.93	19.92
92-09-05	37	15.13	60.15	15.57	33.42	1.65	20.31
92-09-13	45	36.08	45.90	1.66	25.50	1.78	14.33
92-09-28	60	38.27	25.72	3.28	14.29	1.48	9.65
92-10-20	82	34.06	27.77	3.06	15.43	1.37	11.28
92-11-21	114	31.80	23.56	3.68	13.09	1.53	8.55
93-01-14	167	25.95	23.84	0.50	13.24	1.21	10.93
93-03-13	225	27.41	24.76	0.56	13.75	1.34	10.29

Multiple Sample Data

Sample Date	Position	% MC	Avg % VS	S	Avg % C

Pile L3

Sample Date	Days	% MC	Avg % VS	S	Avg % C	% N	Avg C:N ratio
92-08-02	2	46.13	72.35	3.46	40.20	2.32	17.33
92-08-06	6	40.69	61.06	3.77	33.92	1.87	18.11
92-08-11	11	28.85	74.13	4.07	41.18	2.43	16.97
92-08-16	16	41.40	61.84	1.58	34.36	3.24	10.61
92-08-27	27	49.90	63.16	7.80	35.09	2.12	16.58
92-09-05	36	54.73	48.77	2.48	27.09	2.15	12.63
92-09-13	44	43.42	51.50	2.00	28.61	1.91	15.00
92-09-28	59	49.77	34.17	7.88	18.98	1.54	12.34
92-10-20	81	43.49	45.33	0.37	25.18	2.02	12.46
92-11-21	113	34.53	44.60	6.94	24.78	1.77	13.96
93-01-14	166	38.50	29.92	0.85	16.62	1.58	10.49
93-03-13	224	30.20	33.76	0.35	18.75	1.82	10.30

Pile L4

92-08-02	2	57.46	70.19	7.91	38.99	1.97	19.83
92-08-16	16	43.60	53.63	7.98	29.79	2.03	14.71
92-08-27	27	43.96	62.87	1.67	34.93	2.13	16.39
92-09-05	36	37.78	62.75	7.87	34.86	1.69	20.61
92-09-13	44	49.96	55.19	12.31	30.66	2.59	11.86
92-09-28	59	37.44	36.67	2.65	20.37	1.93	10.55
92-10-20	81	37.40	49.29	3.54	27.39	1.93	14.22
92-11-21	113	28.41	35.88	3.47	19.93	2.15	9.26
93-01-14	166	26.35	36.16	0.55	20.09	1.84	10.94
93-03-13	224	21.28	32.64	0.99	18.13	1.67	10.87

Multiple Sample Data

Sample Date	Position	% MC	Avg % VS	S	Avg % C

Pile C1

Sample Date	Days	% MC	Avg % VS	S	Avg % C	% N	Avg C:N ratio
92-08-11	8	48.27	75.74		42.08	2.76	15.27
92-08-16	13	53.63	60.89	26.76	33.83	2.65	12.79
92-09-03	31	43.83	58.05	13.18	32.25	2.42	13.35
92-09-13	41	50.83	52.99	1.23	29.44	2.20	13.39
92-10-02	60	41.65	55.27	2.33	30.71	2.62	11.73
92-10-20	78	32.28	47.39	4.01	26.33	2.86	9.22
92-11-19	108	42.37	61.29	6.70	34.05	2.99	11.39
93-01-14	163	38.74	52.36	0.16	29.09	2.96	9.83
93-03-13	221	33.28	55.61	0.54	30.90	2.79	11.07

Pile C2

Sample Date	Days	% MC	Avg % VS	S	Avg % C	% N	Avg C:N ratio
92-08-11	8	52.46	75.74	6.57	42.08	3.48	12.09
92-08-16	13	52.46	63.37	3.45	35.21	2.29	15.35
92-09-03	31	56.50	52.00	8.80	28.89	2.81	10.30
92-09-13	41	50.73	58.43	4.89	32.46	2.62	12.38
92-10-02	60	48.80	58.44	8.65	32.47	2.66	12.20
92-10-20	78	54.28	47.69	4.32	26.49	2.77	9.56
92-11-19	108	55.64	48.16	3.66	26.76	2.22	12.05
93-01-14	163	47.61	53.36	0.28	29.64	2.83	10.47
93-03-13	221	22.09	36.69	1.52	20.38	2.02	10.12

Multiple Sample Data

Sample Date	Position	% MC	Avg % VS	S	Avg % C

Table A.2 - Multiple Sample % Volatile Solids Statistics

Pile	Sample Date	Mean % VS	S	n	SE of Mean	95 % CI ±	95 % CI % of Mean Value ±
1	92-09-26	47.66	6.73	9	2.24	5.18	10.87
1	92-10-20	37.09	3.24	9	1.08	2.50	6.73
2	92-09-26	34.81	10.31	9	3.44	7.94	22.80
3	92-09-28	34.81	4.78	9	1.59	3.68	10.97
3	92-10-18	38.86	6.05	9	2.02	4.66	11.98
4	92-09-26	39.22	7.43	9	2.48	5.72	14.58
4	92-10-15	33.55	5.71	12	1.65	3.62	10.80
5	92-09-28	36.47	5.68	9	1.89	4.37	11.98
5	92-10-18	43.45	4.15	9	1.38	3.19	7.35
6	92-09-26	52.73	4.29	9	1.43	3.30	6.26
6	92-10-15	48.34	9.65	12	2.79	6.13	12.67
7	92-09-26	35.87	4.27	9	1.42	3.29	9.16
7	92-10-15	32.54	12.82	12	3.70	8.14	25.02
8	92-09-28	32.60	8.42	9	2.81	6.48	19.89
8	92-10-18	36.16	6.47	9	2.16	4.99	13.78
R1	92-10-20	43.74	2.67	9	0.89	2.05	4.69
R2	92-10-20	36.69	5.75	9	1.92	4.42	12.06
						Average	**12.45**

Table A.3 - ANOVA - Mean % Volatile Solids Values

Pile 2

sample date 92-09-26
sample locations X,Y,Z

source of variation	sum of squares	degrees of freedom	mean square	ratio s_L^2/s_R^2	$F_{2,6}$ (0.005)
within location	S_R=414.49	6	s_R^2=69.80	2.10	5.14
between locations	S_L=290.42	2	s_L^2=145.21		cannot reject H_o
total about the grand average	S_D=704.91	8			

Pile 7

sample date 92-10-15
sample locations X,Y,Y',Z

source of variation	sum of squares	degrees of freedom	mean square	ratio s_L^2/s_R^2	$F_{3,8}$ (0.005)
within locations	S_R=1207.01	8	s_R^2=150.87	0.885	4.07
between locations	S_L=400.70	3	s_L^2=133.57		cannot reject H_o
total about the grand average	S_D=1607.71				

Appendix B - Density and Porosity Data

Table B.1 - Compost Densities and Porosity Data

Pile 1

Sample Date	Days	Wet Bulk Density Kg/m^3	Dry Bulk Density Kg/m^3	Sample Date	Avg ρ_c Kg/m^3	S	Porosity
92-08-23	24	307	238	92-08-23	885.5	110.6	0.732
92-09-13	45	419	283	92-09-13	1247.5	46.0	0.773
92-09-28	60	529	369	92-09-26	943.9	2.40	0.609
92-10-20	85	519	355	92-10-20	1000.2	15.7	0.645
92-11-19	112	539	393	92-11-19	1184.5	66.4	0.668
93-01-14	167	599	429	93-01-12	1022.3	26.3	0.580
93-03-13	225	559	471	93-03-13	1030.1	10.0	0.543

Pile 2

92-08-23	23	269	232	92-08-23	737.2	16.5	0.685
92-09-13	44	449	347	92-09-13	779.0	6.6	0.554
92-09-28	59	549	420	92-09-26	955.5	7.3	0.561
92-10-20	84	549	438	92-11-05	1028.4	10.3	0.574
92-11-19	111	659	536	92-11-19	1221.9	11.9	0.561
93-01-14	166	698	518	93-01-12	1211.4	10.9	0.573
93-03-13	224	649	526	93-03-13	1053.3	23.9	0.501

Pile 3

92-08-23	23	409	270	92-08-23	984.4	72.4	0.725
92-09-13	44	524	397	92-09-13	1042.9	12.3	0.620
92-09-28	59	639	417	92-09-28	1124.9	12.7	0.629
92-10-20	84	718	500	92-10-18	1074.8	9.8	0.535
92-11-19	111	738	507	92-11-19	1295.0	30.7	0.608
93-01-14	166	708	493	93-01-14	1263.6	103.4	0.610
93-03-13	224	723	504	93-03-13	1197.4	5.0	0.579

Pile 4

92-08-23	24	249	185	92-08-23	805.8	56.0	0.771
92-09-13	45	429	285	92-09-13	1078.4	117.0	0.736
92-09-28	60	549	360	92-09-26	1234.9	97.3	0.708
92-10-20	85	599	399	92-10-15	1052.6	60.2	0.621
92-11-19	112	669	456	92-11-19	1221.2	15.5	0.626
93-01-14	167	659	456	93-01-12	1172.5	103.0	0.611
93-03-13	225	639	494	93-03-13	1060.1	41.5	0.534

Pile 5

Sample Date	Days	Wet Bulk Density Kg/m^3	Dry Bulk Density Kg/m^3	Sample Date	Avg p_c Kg/m^3	S	Porosity
92-08-23	23	225	148	92-08-23	1063.9	174.7	0.861
92-09-13	44	369	284	92-09-13	946.1	23.3	0.700
92-09-28	59	509	353	92-09-28	976.7	20.6	0.639
92-10-20	84	469	328	92-10-15	1017.3	26.4	0.678
92-11-19	111	659	499	92-11-19	1206.6	6.5	0.587
93-01-14	166	693	504	93-01-14	902.1	103.1	0.441
93-03-13	224	609	517	93-03-13	953.6	10.4	0.458
Pile 6							
92-08-23	24	210	162	92-08-23	677.9	26.3	0.761
92-09-13	45	249	196	92-09-13	805.3	5.6	0.757
92-09-28	60	329	232	92-09-26	884.2	136.9	0.738
92-10-20	85	439	302	92-10-15	971.3	93.4	0.689
92-11-19	112	449	347	92-11-19	1079.2	69.1	0.679
93-01-14	167	524	424	93-01-12	913.5	36.1	0.536
93-03-13	225	564	443	93-03-13	1010.1	22.4	0.561
Pile 7							
92-08-23	24	329	245	92-08-23	991.4	32.5	0.753
92-09-13	45	479	332	92-09-13	1075.3	45.1	0.691
92-09-28	60	679	446	92-09-26	1115.4	65.0	0.600
92-10-20	85	549	356	92-10-15	922.2	62.4	0.614
92-11-19	112	589	416	92-11-19	1038.9	212.4	0.600
93-01-14	167	609	426	93-01-12	1122.4	16.6	0.620
93-03-13	225	589	468	93-03-13	1035.3	70.3	0.548
Pile 8							
92-08-23	23	434	326	92-08-23	518.8	4.2	0.372
92-09-13	44	469	335	92-09-13	1111.3	12.1	0.699
92-09-28	59	649	445	92-09-28	1008.2	7.9	0.559
92-10-20	84	629	446	92-10-18	917.6	96.3	0.514
92-11-19	111	639	471	92-11-19	1239.5	26.6	0.620
93-01-14	166	639	485	93-01-12	1233.6	106.2	0.607
93-03-13	224	619	496	93-03-13	1078.4	29.9	0.540

Pile R1

Sample Date	Days	Wet Bulk Density Kg/m^3	Dry Bulk Density Kg/m^3	Sample Date	Avg ρ_c Kg/m^3	S	Porosity
92-08-23	24	329	226	92-08-23	761.55	39.5	0.703
92-09-13	45	544	361	92-09-13	1006.78	4.7	0.642
92-09-28	60	649	408	92-09-28	1108.48	26.1	0.632
92-10-20	85	569	380	92-10-20	836.45	105.2	0.545
92-11-19	112	599	417	92-11-19	1097.72	41.9	0.620
93-01-14	167	629	439	93-01-12	1280.86	350.9	0.657
93-03-13	225	559	451	93-03-13	1069.25	11.9	0.578

Pile R2

92-08-23	24	374	257	92-08-23	862.00	12.6	0.702
92-09-13	45	554	369	92-09-13	1039.28	6.7	0.645
92-09-28	60	609	421	92-09-28	1050.36	17.2	0.600
92-10-20	85	559	379	92-10-20	956.96	8.9	0.604
92-11-19	112	589	427	92-11-19	1368.04	132.0	0.688
93-01-14	167	659	477	93-01-14	986.08	127.2	0.516
93-03-13	225	698	495	93-03-13	1069.31	87.4	0.537

Pile L1

92-08-23	24	309	203	92-08-27	830.87	19.6	0.756
92-09-13	45	479	311	92-09-13	1102.16	17.4	0.718
92-09-28	60	619	401	92-09-28	1139.35	24.6	0.648
92-10-20	85	728	477	92-10-20	1209.07	34.6	0.605
92-11-19	112	798	549	92-11-21	1154.14	43.9	0.524
93-01-14	167	808	577	93-01-14	1168.88	74.6	0.506
93-03-13	225	753	641	93-03-13	1018.26	270.4	0.371

Pile L2

92-08-23	24	319	223	92-08-27	772.12	152.7	0.711
92-09-13	45	359	264	92-09-13	873.00	20.4	0.698
92-09-28	60	529	382	92-09-28	1197.36	2.4	0.681
92-10-20	85	659	491	92-10-20	974.34	221.9	0.496
92-11-19	112	669	507	92-11-21	1156.13	66.5	0.561
93-01-14	167	649	515	93-01-14	1140.82	51.6	0.549
93-03-13	225	659	517	93-03-13	1156.72	170.0	0.553

Pile L3

Sample Date	Days	Wet Bulk Density Kg/m^3	Dry Bulk Density Kg/m^3	Sample Date	Avg ρc Kg/m^3	S	Porosity
92-08-23	23	329	220	92-08-27	844.9	30.0	0.740
92-09-13	44	499	348	92-09-13	1089.8	14.2	0.681
92-09-28	59	688	460	92-09-28	1107.1	10.3	0.585
92-10-20	84	599	417	92-10-20	1117.2	50.1	0.627
92-11-19	111	629	467	92-11-21	1147.1	104.6	0.593
93-01-14	166	748	540	93-01-14	1058.8	16.5	0.490
93-03-13	224	728	559	93-03-13	1036.9	49.6	0.460

Pile L4

92-08-23	23	299	208	92-08-27	777.3	126.3	0.732
92-09-13	44	337	225	92-09-13	1114.7	94.6	0.799
92-09-28	59	439	319	92-09-28	1262.8	17.2	0.747
92-10-20	84	479	349	92-10-20	1066.1	33.5	0.673
92-11-19	111	599	466	92-11-21	1053.6	112.2	0.558
93-01-14	166	619	490	93-01-14	891.2	10.7	0.451
93-03-13	224	629	518	93-03-13	1029.9	10.9	0.497

Pile C1

92-08-23	20	329	221	92-09-03	844.1	13.4	0.738
92-09-13	41	384	255	92-09-13	1056.5	39.6	0.759
92-09-28	56	399	282	92-10-02	1050.8	7.9	0.732
92-10-20	78	389	294	92-10-20	1027.7	15.2	0.714
92-11-19	108	399	280	92-11-19	967.7	91.7	0.710
93-01-14	163	469	338	93-01-14	1040.2	137.3	0.675
93-03-13	221	449	337	93-03-13	973.9	176.3	0.654

Pile C2

92-08-23	20	339	226	92-09-03	832.2	10.7	0.728
92-09-13	41	399	265	92-09-13	976.1	6.6	0.729
92-09-28	56	379	255	92-10-02	1052.2	11.4	0.758
92-10-20	78	359	233	92-10-20	1026.3	52.6	0.773
92-11-19	108	299	221	92-11-19	1148.0	25.4	0.808
93-01-14	163	459	311	93-01-14	911.4		0.659
93-03-13	221	449	368	93-03-13	1140.3	31.2	0.677

Appendix C - Water Extract Parameter Data

Table C.1 - Water Extract Parameter Data

Pile 1

Date	Days	Avg TOC	n	S	Avg NH3	Avg Org N	n	S	TOC/ Org N
		mg/l			mg/l	mg/l			
92-08-02	3	5499.49	3	8.54					
92-08-11	12	3913.53	2	12.02	38.29	369.10	2	9.16	10.60
92-08-23	24	2656.30	3	6.66	33.64	310.82	2	3.99	8.55
92-09-02	34	1271.76	3	9.54	10.14	112.76	2	1.79	11.28
92-09-13	45	2137.49	3	2.83	35.20	217.70	2	0.69	9.82
92-09-26	58	1957.72	3	10.69	24.54	210.78	3	7.04	9.29
92-10-18	82	1245.23	2	2.12	6.87	145.73	2	0.64	8.54
92-11-19	112	1091.20	6	15.74	5.75	113.55	2	0.12	9.61
93-01-12	165	1016.90	3	1.15	8.79	110.20	2	0.23	9.23
93-03-13	225	1017.79	3	12.28	22.97	120.61	3	1.33	8.44
Pile 2									
92-08-03	2	2644.18	3	4.51	33.73	270.67	1		9.77
92-08-11	11	2919.19	5	1005.0	63.36	292.78	1		9.97
92-08-23	23	1783.35	6	16.34	27.88	164.42	2	0.79	10.85
92-09-04	35	2301.76	6	131.86	23.93	213.55	2	1.00	10.78
92-09-13	44	1447.59	6	475.52	22.66	103.61	2	1.20	13.97
92-09-26	57	846.05	3	4.15	22.91	74.61	4	2.51	11.34
92-11-05	97	527.11	8	53.05	28.68	44.35	4	6.13	11.89
92-11-19	111	496.70	2	3.04	16.62	38.27	5	5.30	12.98
93-01-12	164	649.81	3	8.21	25.17	72.98	2	0.80	8.90
93-03-13	224	402.07	2	1.45	22.28	53.63	5	5.64	7.50
Pile 3									
92-08-02	2	4179.30	3	27.88					
92-08-11	11	4137.69	3	3.54	17.19	265.74	3	61.82	15.57
92-08-23	23	3815.24	3	12.00	37.38	469.42	3	70.87	8.13
92-09-05	35	2749.44	3	8.14	57.25	244.27	3	51.39	11.26
92-09-13	44	1880.56	3	19.92	47.35	195.56	2	35.28	9.62
92-09-28	59	881.42	3	4.07	27.57	84.46	2	1.99	10.44
92-10-18	79	794.69	4	111.72	15.15	76.63	5	11.40	10.37
92-11-19	111	776.34	3	6.47	6.95	85.45	2	44.21	9.09
92-01-14	166	728.50	3	1.64	16.3	77.41	2	39.12	9.41
92-03-13	224	649.61	12	13.10	13.53	98.54	4	11.79	6.59
Pile 4									
92-08-03	4	2053.70	1						
92-08-11	12	2786.55	2	4.95	57.86	309.64	1		9.00
92-08-23	24	2483.87	3	7.23	20.92	238.06	3	59.21	10.43
92-09-02	34	2019.64	5	7.29	34.72	231.27	3	16.80	8.73
92-09-13	45	1154.15	5	9.82	20.06	87.28	2	1.99	13.22
92-09-26	58	845.49	3	3.83	9.86	81.65	2	0.00	10.36
92-10-15	77	703.60	8	41.82	4.92	81.15	4	19.39	8.67
92-11-19	112	666.37	3	5.25	2.65	64.33	5	10.70	10.36
93-01-12	165	830.41	3	3.00	-0.04	76.51	4	2.21	10.85

93-03-13	225	793.91	3	5.50	9.99	89.97	6	11.39	8.82

Pile 5

Date	Days	Avg TOC	n	S	Avg NH3	Avg Org N	n	S	TOC/ Org N
		mg/l			mg/l	mg/l			
92-08-02	2	3778.14	3	50.34					
92-08-11	11	3913.80	3	25.11	8.45	416.68	1		9.39
92-08-23	23	3411.28	3	17.62	82.21	316.59	2	0.59	10.78
92-09-04	35	1238.86	2	2.12	9.29	109.38	2	1.39	11.33
92-09-13	44	1846.39	2	0.71	26.89	197.08	1		9.37
92-09-28	59	1518.45	3	9.85	12.39	157.38	2	1.99	9.65
92-10-18	79	1056.51	4	55.94	3.57	125.38	3	6.28	8.43
92-11-19	111	896.36	6	81.37	2.65	87.17	2	1.75	10.28
93-01-14	166	847.07	3	2.35	4.17	94.15	2	5.57	9.00
93-03-13	224	751.98	6	11.02	20.50	83.23	2	0.80	9.03
Pile 6									
92-08-03	4	3136.96	3	9.07					
92-08-11	12	4097.17	2	3.54	43.36	419.49	1		9.77
92-08-23	24	2893.69	3	0.58	21.54	313.92	2	1.99	9.22
92-09-02	34	1117.93	3	21.52	18.86	195.11	1		5.73
92-09-13	45	1648.26	3	5.20	13.56	155.13	2	8.36	10.63
92-09-26	58	2260.53	3	3.61	37.45	210.59	4	7.88	10.73
92-10-15	77	1125.69	6	18.49	10.25	93.70	3	0.32	12.01
92-11-19	112	1082.62	3	8.39	2.73	99.47	4	1.89	10.88
93-01-12	165	1168.86	3	6.35	9.05	102.41	3	4.51	11.41
93-03-13	225	996.74	8	32.73	15.66	100.89	4	4.64	9.88
Pile 7									
92-08-02	3	3940.59	3	18.04					
92-08-11	12	4255.97	2	5.66	16.89	420.62	1		10.12
92-08-23	24	3644.48	3	14.98	17.46	410.35	2	2.99	8.88
92-09-02	34	1898.47	2	12.02	26.64	167.59	2	0.10	11.33
92-09-13	45	1458.33	3	5.13	5.77	167.24	2	1.20	8.72
92-09-26	58	847.67	3	4.48	5.21	83.48	2	0.20	10.15
92-10-15	77	898.13	5	98.99	0.56	95.24	3	12.48	9.43
92-11-19	112	719.62	6	68.38	4.00	65.32	2	0.16	11.02
93-01-12	165	900.89	3	2.08	6.42	90.09	1		10.00
93-03-13	225	857.24	6	18.28	27.71	99.78	2	0.32	8.59
Pile 8									
92-08-02	2	3124.70	3	10.82					
92-08-11	11	1655.06	3	4.24	30.97	149.22	1		11.09
92-08-23	23	2746.05	3	5.03	33.78	164.00	1		16.74
92-09-04	35	2852.98	2	21.92	110.65	336.72	2	2.39	8.47
92-09-13	44	1142.96	2	6.36	6.90	103.61	2	0.00	11.03
92-09-28	59	534.09	3	4.88	10.14	47.58	2	1.19	11.23
92-10-18	79	587.90	5	48.38	6.09	56.68	3	2.65	10.37
92-11-19	111	474.05	3	4.43	6.37	38.63	2	2.39	12.27
93-01-12	164	507.53	3	5.39	12.93	68.50	2	3.07	7.41
93-03-13	224	438.63	6	1.81	9.52	47.52	2	0.64	9.23

Pile R1

Date	Days	Avg TOC mg/l	n	S	Avg NH3 mg/l	Avg Org N mg/l	n	S	TOC/ Org N
92-08-02	3	3724.30	3	13.22					
92-08-11	12	3382.30	3	19.36	40.54	326.59	1		10.36
92-08-23	24	3705.60	3	9.60	47.30	411.05	1		9.01
92-09-05	37	1712.80	3	2.89	49.84	189.20	2	0.40	9.05
92-09-13	45	2725.40	3	8.08	21.54	317.58	2	16.72	8.58
92-09-28	60	1189.00	2	2.12	13.65	134.44	2	10.95	8.84
92-10-20	82	797.30	3	36.41	11.58	99.24	2	6.97	8.03
92-11-19	112	843.70	3	5.63	9.71	84.25	2	0.30	10.01
93-01-12	165	893.80	3	4.77	15.07	87.99	2	1.00	10.16
93-03-13	225	716.20	3	7.69	20.84	83.62	2	6.77	8.56
Pile R2									
92-08-02	3	2412.40	3	10.22					
92-08-11	12	4670.20	3	5.65	22.52	568.71	1		8.21
92-08-23	24	2996.40	3	8.12	55.89	269.44	2	1.20	11.12
92-09-05	37	1683.20	3	15.28	46.74	187.22	1		8.99
92-09-13	45	2761.20	3	6.43	24.35	331.24	2	11.35	8.34
92-09-26	60	834.30	3	4.10	19.29	83.06	2	5.98	10.04
92-10-20	82	482.50	3	1.84	8.45	36.46	2	0.20	13.23
92-11-19	112	845.40	3	1.62	12.67	104.03	2	0.20	8.13
93-01-12	165	897.90	3	5.55	8.73	86.29	2	0.20	10.41
93-03-13	225	756.60	3	9.36	23.79	82.84	4	8.51	9.13
Pile L1									
92-08-02	3	3536.28	3	6.35					
92-08-11	12	2760.05	3	17.44	34.21	356.01	2	12.14	7.75
92-08-16	17	3447.48	3	7.78	73.48	373.04	1		9.24
92-08-27	28	3054.08	3	29.82	33.37	297.73	2	1.00	10.26
92-09-05	37	1107.41	3	8.62	16.61	99.67	1		11.11
92-09-13	45	1878.20	3	3.51	34.35	146.68	2	0.00	12.80
92-09-28	60	1239.09	3	6.24	7.04	101.35	2	0.00	12.23
92-10-20	82	688.37	3	3.34	2.96	67.57	2	3.99	10.19
92-11-21	114	703.64	3	1.30	30.41	125.99	2	0.99	5.58
93-01-14	167	710.88	3	3.65	11.41	89.04	2	0.49	7.98
93-03-13	225	571.39	3	7.90	20.13	91.36	3	0.20	6.25
Pile L2									
92-08-02	3	3608.84	2	1.41					
92-08-16	17	2859.74	2	38.18	62.37	292.80	2	0.00	9.77
92-08-27	28	3144.29	3	29.61	10.56	354.88	2	0.20	8.86
92-09-05	37	1825.29	2	1.41	28.15	166.67	1		10.95
92-09-13	45	1968.80	3	9.85	35.05	201.51	2	0.30	9.77
92-09-28	60	745.19	3	3.59	30.13	122.47	2	1.99	6.08
92-10-20	82	695.80	3	8.49	9.86	57.86	2	0.20	12.03
92-11-21	114	857.51	3	1.25	34.98	96.85	2	1.60	8.85
92-01-14	167	569.68	3	7.90	19.78	61.80	2	0.20	9.22

93-03-13	225	646.14	3	6.57	21.68	69.96	2	2.59	9.24

Pile L3

Date	Days	Avg TOC	n	S	Avg NH3	Avg Org N	n	S	TOC/ Org N
		mg/l			mg/l	mg/l			
92-08-02	2	3602.14	2	19.09					
92-08-11	11	4154.76	3	5.86	91.22	470.17	1		8.84
92-08-16	16	3193.99	3	30.62	34.07	309.98	2	0.40	10.30
92-08-27	27	3264.74	3	11.02	24.11	359.53	2	6.77	9.08
92-09-05	36	2591.72	3	10.10	41.53	275.49	2	10.55	9.41
92-09-13	44	2579.81	3	3.21	43.64	247.83	2	0.50	10.41
92-09-28	59	1034.46	3	2.08	9.43	119.66	2	0.40	8.64
92-10-20	81	1491.50	6	180.85	6.33	130.64	2	12.34	11.42
92-11-21	113	1266.63	3	1.00	33.43	153.72	2	0.40	8.24
92-01-14	166	794.65	3	2.80	10.98	95.72	2	0.00	8.30
93-03-13	224	944.36	3	3.19	18.79	113.32	2	0.20	8.33
Pile L4									
92-08-02	2	3735.89	2	9.90	34.07	447.93	2	0.40	8.34
92-08-16	16	3536.17	3	8.50	45.33	434.98	1		8.13
92-08-27	27	3483.75	3	32.15	7.18	378.81	2	0.20	9.20
92-09-05	36	4197.92	3	22.22	184.76	368.82	2	1.99	11.38
92-09-13	44	1851.87	3	3.79	140.07	448.35	2	0.20	4.13
92-09-28	59	1939.16	3	7.81	43.22	227.06	2	0.20	8.54
92-10-20	81	2061.95	2	1.41	8.45	168.45	3	26.43	12.24
92-11-21	113	1752.69	4	20.66	61.19	215.47	3	12.28	8.13
92-01-14	166	1591.12	3	1.15	39.00	152.46	2	3.39	10.44
93-03-13	224	1195.03	3	4.73	33.93	130.92	1		9.13

Appendix D - Temperature and Oxygen Data and Plots

Table D.1 - Pile Temperature and Oxygen Data

Pile 1

Date	Days	Avg Pile Temp θ C	Avg Pile % Oxygen
92-08-01	2	67.5	
92-08-03	4	63.2	
92-08-05	6	67.6	
92-08-07	8	61.6	
92-08-10	11	58.6	
92-08-11	12	61.9	
92-08-12	13	59.2	
92-08-13	14	65.1	
92-08-14	15	68.3	14.2
92-08-15	16	72.3	
92-08-16	17	66.8	15.4
92-08-17	18	66.5	
92-08-20	21	55.6	17.5
92-08-22	23	52.1	14.4
92-08-25	26	55.9	16.6
92-08-27	28	50.9	
92-08-29	30	54.3	
92-08-31	32	40.9	15.7
92-09-03	35	64.0	14.5
92-09-05	37	61.0	17.5
92-09-07	39	57.2	
92-09-13	45	58.0	20.4
92-09-17	49	55.5	20.0
92-09-20	52	48.5	
92-09-23	55	58.7	12.4
92-09-28	60	61.5	18.5
92-10-05	67	40.5	18.8
92-10-11	73	26.1	19.4
92-10-12	74	27.5	
92-10-13	75	29.0	
92-10-15	77	34.4	
92-10-16	78	41.3	
92-10-18	80	39.5	
92-10-22	84	33.3	
92-10-26	88	28.9	
92-11-01	94	54.0	
92-11-04	97	59.4	18.2
92-11-07	100	57.1	
92-11-11	104	64.5	16.1
92-11-15	108	57.5	
92-11-19	112	54.5	
92-11-22	115	49.5	
92-11-23	116	47.0	
92-12-02	124	43.5	15.0

Pile 2

Date	Days	Avg Pile Temp θ C	Avg Pile % Oxygen
92-08-02	2	64.1	
92-08-04	4	67.1	
92-08-05	5	68.5	
92-08-06	6	62.0	
92-08-07	7	65.7	
92-08-10	10	62.9	
92-08-11	11	60.2	
92-08-12	12	56.8	
92-08-13	13	62.8	
92-08-14	14	66.6	
92-08-15	15	68.1	
92-08-16	16	64.1	14.0
92-08-17	17	52.6	18.2
92-08-20	20	58.7	
92-08-22	22	50.1	19.4
92-08-25	25	45.2	19.1
92-08-27	27	43.7	
92-08-29	29	37.8	
92-08-31	31	30.3	19.3
92-09-05	36	48.4	20.1
92-09-07	38	57.2	
92-09-13	44	31.1	20.1
92-09-17	48	25.0	20.0
92-09-19	50	52.6	
92-09-20	51	32.3	
92-09-23	54	55.5	16.7
92-09-28	59	54.0	16.7
92-10-05	66	47.5	14.8
92-10-11	72	31.0	20.2
92-10-12	73	28.5	
92-10-13	74	29.5	
92-10-15	76	36.8	
92-10-16	77	36.0	
92-10-18	79	35.1	
92-10-22	84	30.8	
92-10-26	87	32.4	
92-11-01	93	54.0	
92-11-04	96	60.2	
92-11-07	99	53.6	
92-11-11	103	54.1	12.9
92-11-15	107	58.5	
92-11-19	111	54.0	
92-11-22	114	52.0	
92-11-23	115	50.5	13.7

92-12-09	131	40.5	17.3
92-12-17	139	38.0	19.5
92-12-23	146	36.5	20.4
93-01-03	156	25.5	20.6
93-01-10	163	19.0	20.6
93-01-17	170	13.0	20.7
93-01-21	174	16.0	20.7
93-01-28	181	11.5	20.8
93-02-03	187	9.5	20.6
93-02-11	195	5.0	20.9
93-02-18	202	5.8	20.8
93-02-25	209	3.8	20.9
93-03-10	222	4.0	20.9
93-03-18	230	4.0	20.8
93-04-06	249	6.5	
93-04-20	263	8.5	20.7
93-05-11	284	14.0	20.6

92-12-02	123	48.0	13.4
92-12-09	130	46.5	16.2
92-12-17	138	38.5	18.5
92-12-23	144	33.0	20.3
93-01-03	155	24.5	20.6
93-01-10	162	8.8	20.5
93-01-17	169	9.5	20.7
93-01-21	173	14.0	20.9
93-01-28	180	9.5	20.8
93-02-03	186	6.8	20.8
93-02-11	194	2.3	20.7
92-02-18	201	2.5	20.8
92-02-25	208	1.5	20.8
93-03-10	221	5.0	20.9
93-03-18	229	2.3	20.9
93-03-30	241	6.5	20.8
93-04-06	248	7.5	
93-04-20	262	9.3	20.9
93-05-11	283	14.5	20.7

Pile 3

Date	Days	Avg Pile Temp ^{0}C	Avg Pile % Oxygen
92-08-02	2	64.3	
92-08-04	4	63.5	
92-08-05	5	69.7	
92-08-07	7	59.0	
92-08-10	10	55.4	
92-08-11	11	63.4	
92-08-12	12	55.7	
92-08-13	13	65.9	
92-08-14	14	66.9	
92-08-15	15	68.7	
92-08-16	16	68.8	15.9
92-08-17	17	65.4	17.4
92-08-20	20	64.3	
92-08-22	22	62.6	16.6
92-08-25	25	57.0	18.3
92-08-27	27	50.9	
92-08-29	29	37.7	
92-08-31	31	34.2	15.9
92-09-05	36	64.8	15.4
92-09-09	40	62.3	
92-09-13	44	59.8	18.3
92-09-17	48	46.0	19.6
92-09-19	50	51.5	
92-09-20	51	27.3	
92-09-23	54	47.0	16.5

Pile 4

Date	Days	Avg Pile Temp ^{0}C	Avg Pile % Oxygen
92-08-01	2	63.0	
92-08-03	4	68.0	
92-08-05	6	67.6	
92-08-07	8	62.7	
92-08-10	11	63.7	
92-08-11	12	66.6	
92-08-12	13	54.2	
92-08-13	14	64.1	
92-08-14	15	67.7	
92-08-15	16	69.2	
92-08-16	17	64.1	15.5
92-08-17	18	67.9	
92-08-20	21	56.3	17.5
92-08-22	23	56.3	17.0
92-08-25	26	56.8	17.2
92-08-29	30	53.2	
92-08-31	32	45.0	13.2
92-09-05	37	63.5	13.7
92-09-07	39	57.9	
92-09-13	45	49.0	17.6
92-09-17	49	50.5	18.0
92-09-19	51	59.0	
92-09-20	52	29.5	
92-09-23	55	48.5	16.0
92-09-28	60	50.8	16.8

92-09-28	59	51.9	17.6
92-10-05	66	37.4	14.7
92-10-11	72	36.4	20.3
92-10-12	73	32.5	
92-10-13	74	29.5	
92-10-15	76	30.0	
92-10-16	77	14.7	
92-10-18	79	21.4	
92-10-22	84	35.0	
92-10-26	87	31.7	
92-11-01	93	54.0	
92-11-04	96	67.6	
92-11-07	99	61.3	
92-11-11	103	67.5	16.2
92-11-15	107	57.0	
92-11-19	111	55.5	
92-11-22	114	56.0	
92-11-23	115	55.0	16.6
92-12-02	123	55.5	16.2
92-12-09	130	53.5	16.9
92-12-17	138	43.0	19.2
92-12-23	144	41.0	20.5
93-01-03	155	37.0	20.6
93-01-10	162	28.5	20.6
93-01-17	169	26.5	20.8
93-01-21	173	16.5	20.9
93-01-28	180	11.8	20.7
93-02-03	186	7.8	20.9
93-02-11	194	5.8	20.6
93-02-18	201	7.0	20.7
93-02-25	208	4.5	20.8
93-03-10	221	6.8	20.3
93-03-18	229	4.0	20.4
93-03-30	241	6.8	20.9
93-04-06	248	7.0	
93-04-20	262	10.8	20.9
93-05-11	283	13.5	20.4

92-10-05	67	47.0	11.7
92-10-11	73	33.0	17.9
92-10-12	74	31.0	
92-10-13	75	29.5	
92-10-15	77	24.0	
92-10-16	78	23.9	
92-10-18	80	26.9	
92-10-22	84	29.8	
92-10-26	88	29.6	
92-11-01	94	54.0	
92-11-04	97	61.3	17.0
92-11-07	100	60.6	
92-11-11	104	56.3	16.1
92-11-15	108	56.0	
92-11-19	112	53.0	
92-11-22	115	47.0	
92-11-23	116	47.0	
92-12-02	124	37.5	16.2
92-12-09	131	35.5	17.7
92-12-17	139	32.5	19.1
92-12-23	146	31.0	20.4
93-01-03	156	26.5	20.7
93-01-10	163	24.0	20.4
93-01-17	170	21.0	20.8
93-01-21	174	9.5	20.9
93-01-28	181	6.8	20.7
93-02-03	187	5.8	20.7
93-02-11	195	7.0	20.8
93-02-18	202	6.0	20.8
93-02-25	209	3.0	20.8
93-03-10	222	6.0	20.9
93-03-18	230	1.5	20.9
93-03-30	242	6.5	20.7
93-04-06	249	7.3	
93-04-20	263	9.0	20.9
93-05-11	284	15.0	20.3

Pile 5

Date	Days	Avg Pile Temp ^{0}C	Avg Pile % Oxygen
92-08-02	2	64.1	
92-08-04	4	67.1	
92-08-05	5	68.5	
92-08-06	6	62.0	

Pile 6

Date	Days	Avg Pile Temp ^{0}C	Avg Pile % Oxygen
92-08-01	2	67.5	
92-08-03	4	63.2	
92-08-05	6	67.6	
92-08-07	8	61.6	

92-08-07	7	65.7		92-08-10	11	58.6	
92-08-10	10	62.9		92-08-11	12	61.9	
92-08-11	11	60.2		92-08-12	13	59.2	
92-08-12	12	56.8		92-08-13	14	65.1	
92-08-13	13	62.8		92-08-14	15	68.3	
92-08-14	14	66.6		92-08-15	16	72.3	
92-08-15	15	68.1		92-08-16	17	66.8	15.0
92-08-16	16	64.1	12.5	92-08-17	18	66.5	
92-08-17	17	52.6	19.5	92-08-20	21	55.6	16.7
92-08-20	20	58.7		92-08-22	23	52.1	17.8
92-08-22	22	50.1	17.0	92-08-25	26	55.9	17.9
92-08-25	25	45.2		92-08-27	28	50.9	
92-08-27	27	43.7		92-08-29	30	54.3	
92-08-29	29	37.8		92-08-31	32	40.9	17.3
92-08-31	31	30.3	17.8	92-09-03	35	64.0	16.5
92-09-05	36	48.4	17.0	92-09-05	37	61.0	18.8
92-09-07	38	57.2		92-09-07	39	57.2	
92-09-13	44	31.1	20.4	92-09-13	45	58.0	18.4
92-09-17	48	25.0	20.3	92-09-17	49	55.5	16.3
92-09-19	50	52.6		92-09-20	52	48.5	
92-09-20	51	32.3		92-09-23	55	58.7	16.0
92-09-23	54	55.5	15.7	92-09-28	60	61.5	19.1
92-09-28	59	54.0	17.4	92-10-05	67	40.5	16.5
92-10-05	66	47.5	18.3	92-10-11	73	26.1	19.2
92-10-11	72	31.0	19.1	92-10-12	74	27.5	
92-10-12	73	28.5		92-10-13	75	29.0	
92-10-13	74	29.5		92-10-15	77	34.4	
92-10-15	76	36.8		92-10-16	78	41.3	
92-10-16	77	36.0		92-10-18	80	39.5	
92-10-18	79	35.1		92-10-22	84	33.3	
92-10-22	84	30.8		92-10-26	88	28.9	
92-10-26	87	32.4		92-11-01	94	54.0	
92-11-01	93	54.0		92-11-04	97	59.4	19.0
92-11-04	96	60.2		92-11-07	100	57.1	
92-11-07	99	53.6		92-11-11	104	64.5	19.0
92-11-11	103	54.1	19.5	92-11-15	108	51.0	
92-11-15	107	59.5		92-11-19	112	45.5	
92-11-19	111	46.5		92-11-22	115	42.5	
92-11-22	114	47.0		92-11-23	116	46.0	17.5
92-11-23	115	42.0	17.9	92-12-02	124	31.5	16.8
92-12-02	123	52.5	18.1	92-12-09	131	28.0	18.0
92-12-09	130	39.0	18.6	92-12-17	139	19.0	20.2
92-12-17	138	32.5	19.8	92-12-23	146	12.0	20.3
92-12-23	144	25.0	20.6	93-01-03	156	13.0	20.4
93-01-03	155	22.5	20.4	93-01-10	163	5.0	20.5
93-01-10	162	15.0	20.3	93-01-17	170	3.5	20.8
93-01-17	169	10.5	20.5	93-01-21	174	3.0	20.9
93-01-21	173	2.5	20.8	93-01-28	181	1.5	20.9
93-01-28	180	3.0	20.8	93-02-03	187	2.0	20.9
93-02-03	186	4.0	20.9	93-02-11	195	4.0	20.7
93-02-11	194	6.5	20.9	93-02-18	202	2.8	20.8
93-02-18	201	6.0	20.9	93-02-25	209	2.5	20.9
93-02-25	208	3.0	20.8	93-03-10	222	5.0	20.8

93-03-10	221	4.5	20.7	93-03-18	230	3.3	20.9
93-03-18	229	2.5	20.6	93-03-30	242	7.5	20.8
93-03-30	241	6.5	20.9	93-04-06	249	8.5	
93-04-06	248	7.5		93-04-20	263	11.5	20.7
93-04-20	262	11.3	20.9	93-05-11	284	23.0	20.2
93-05-11	283	16.8	20.5				

Pile 7

Date	Days	Avg Pile Temp ^{0}C	Avg Pile % Oxygen
92-07-31	1	67.5	
92-08-01	2	63.0	
92-08-03	4	62.5	
92-08-05	6	68.7	
92-08-07	8	65.0	
92-08-10	11	61.1	
92-08-11	12	67.3	
92-08-12	13	58.5	
92-08-13	14	66.5	
92-08-14	15	69.8	14.6
92-08-15	16	70.6	
92-08-16	17	66.3	14.6
92-08-17	18	63.2	
92-08-20	21	61.3	17.5
92-08-22	23	49.4	15.1
92-08-25	26	48.0	15.9
92-08-27	28	49.8	
92-08-29	30	52.9	
92-08-31	32	40.9	17.0
92-09-06	38	56.9	14.5
92-09-13	45	56.0	17.6
92-09-17	49	60.8	19.9
92-09-19	51	59.2	
92-09-20	52	56.8	
92-09-23	55	62.5	15.8
92-09-28	60	52.5	18.3
92-10-05	67	47.0	17.4
92-10-11	73	53.0	19.4
92-10-12	74	50.5	
92-10-13	75	45.0	
92-10-15	77	50.5	
92-10-16	78	45.2	
92-10-18	80	45.8	
92-10-22	84	52.3	
92-10-26	88	54.3	
92-11-01	94	54.0	
92-11-04	97	57.2	17.5
92-11-07	100	52.6	
92-11-11	104	53.5	20.1

Pile 8

Date	Days	Avg Pile Temp ^{0}C	Avg Pile % Oxygen
92-08-02	2	62.8	
92-08-04	4	66.8	
92-08-05	5	70.3	
92-08-07	7	53.5	
92-08-10	10	64.8	
92-08-11	11	65.8	
92-08-12	12	62.3	
92-08-13	13	67.4	
92-08-14	14	63.0	
92-08-15	15	70.0	
92-08-16	16	63.0	14.5
92-08-17	17	62.7	15.0
92-08-20	20	55.5	
92-08-22	22	66.9	17.6
92-08-25	25	56.3	16.1
92-08-27	27	61.0	
92-08-29	29	54.6	
92-08-31	31	40.0	16.7
92-09-05	36	46.2	14.2
92-09-09	40	53.5	
92-09-13	44	67.4	16.7
92-09-17	48	46.2	17.1
92-09-19	50	46.2	
92-09-20	51	30.3	
92-09-23	54	53.9	16.5
92-09-28	59	46.0	16.2
92-10-05	66	44.0	14.1
92-10-11	72	42.5	20.2
92-10-12	73	43.0	
92-10-13	74	29.5	
92-10-15	76	26.0	
92-10-16	77	28.2	
92-10-18	79	41.2	
92-10-22	83	47.8	
92-10-26	87	55.9	
92-11-01	93	54.0	
92-11-04	96	55.6	
92-11-07	99	60.9	
92-11-11	103	62.4	19.6

92-11-15	108	57.0		92-11-15	107	61.5	
92-11-19	112	51.0		92-11-19	111	64.0	
92-11-22	115	50.5		92-11-22	114	61.5	
92-11-23	116	49.0	16.3	92-11-23	115	56.5	
92-12-02	124	40.5	15.0	92-12-02	123	52.5	17.1
92-12-09	131	38.0	17.6	92-12-09	130	50.8	18.3
92-12-17	139	35.5	19.6	92-12-17	138	48.5	20.3
92-12-23	146	34.5	20.5	92-12-23	144	47.5	20.6
93-01-03	156	33.5	20.6	93-01-03	155	46.0	20.5
93-01-10	163	24.5	20.6	93-01-10	162	39.5	20.5
93-01-17	170	22.0	20.8	93-01-17	169	43.0	20.7
93-01-21	174	18.0	20.8	93-01-21	173	41.0	20.9
93-01-28	181	15.8	20.9	93-01-28	180	30.3	20.8
93-02-03	187	11.8	20.7	93-02-03	186	23.5	20.7
93-02-11	195	7.0	20.7	93-02-11	194	12.0	20.8
93-02-18	202	6.8	20.7	92-02-18	201	9.0	20.7
93-02-25	209	5.3	20.9	92-02-25	208	4.8	20.8
93-03-10	222	6.5	20.9	93-03-10	221	6.5	20.3
93-03-18	230	5.5	20.9	93-03-18	229	6.0	20.0
93-03-30	242	6.0	20.7	93-03-30	241	9.0	20.9
93-04-06	249	8.5		93-04-06	248	9.5	
93-04-20	263	10.3	20.8	93-04-20	262	10.5	20.8
93-05-11	284	12.5	20.3	93-05-11	283	14.0	20.6

Pile R1

Date	Days	Avg Pile Temp ^{0}C	Avg Pile % Oxygen
92-08-01	2	64.5	
92-08-03	4	67.1	
92-08-05	6	70.0	
92-08-07	8	72.1	
92-08-10	11	68.3	
92-08-11	12	68.5	
92-08-12	13	64.6	
92-08-13	14	67.9	
92-08-14	15	69.2	13.7
92-08-15	16	71.3	
92-08-16	17	68.3	15.0
92-08-17	18	67.3	
92-08-20	21	60.7	16.4
92-08-22	23	69.3	13.5
92-08-25	26	63.8	
92-08-29	30	61.2	
92-08-31	32	63.7	13.1
92-09-03	35	60.0	9.2
92-09-05	37	65.1	12.6
92-09-07	39	63.9	
92-09-13	45	56.4	12.6
92-09-17	49	61.5	17.6

Pile R2

Date	Days	Avg Pile Temp ^{0}C	Avg Pile % Oxygen
92-08-01	2	68.5	
92-08-03	4	65.8	
92-08-05	6	70.9	
92-08-07	8	71.9	
92-08-10	11	67.9	
92-08-11	12	68.3	
92-08-12	13	63.0	
92-08-13	14	66.5	
92-08-14	15	69.0	
92-08-15	16	69.7	
92-08-16	17	66.1	15.0
92-08-17	18	68.8	
92-08-20	21	59.1	13.2
92-08-22	23	66.6	12.9
92-08-25	26	64.3	15.2
92-08-29	30	66.9	
92-08-31	32	64.8	11.0
92-09-03	35	59.3	8.4
92-09-05	37	64.9	14.7
92-09-07	39	63.4	
92-09-13	45	58.5	14.5
92-09-17	49	60.0	16.0

92-09-19	51	47.7	
92-09-20	52	42.0	
92-09-23	55	43.0	14.3
92-09-28	60	51.8	18.0
92-10-05	67	44.5	15.1
92-10-11	73	43.1	19.4
92-10-12	74	35.5	
92-10-13	75	29.5	
92-10-15	77	36.8	
92-10-16	78	16.2	
92-10-18	80	17.0	
92-10-22	84	22.0	
92-10-26	88	24.8	
92-11-01	94	54.0	
92-11-04	97	54.1	17.6
92-11-07	100	52.9	
92-11-11	104	57.0	18.9
92-11-15	108	61.5	
92-11-19	112	45.5	
92-11-22	115	42.0	
92-11-23	116	46.5	
92-12-02	124	40.0	20.4
92-12-09	131	35.0	20.4
92-12-17	139	28.0	20.6
92-12-23	146	24.5	20.2
93-01-03	156	22.0	20.5
93-01-10	163	16.0	20.4
93-01-17	170	11.0	20.4
93-01-21	174	5.5	20.9
93-01-28	181	4.0	20.9
93-02-03	187	3.0	20.7
93-02-11	195	4.3	20.6
93-02-18	202	4.0	20.9
93-02-25	209	2.5	20.8
93-03-10	222	1.5	20.8
93-03-18	230	1.5	20.9
93-03-30	242	6.8	20.9
93-04-06	249	7.0	
93-04-20	263	7.0	20.8
93-05-11	284	10.5	20.7

92-09-19	51	60.5	
92-09-20	52	42.0	
92-09-23	55	46.5	14.4
92-09-28	60	48.2	17.6
92-10-04	66	54.1	
92-10-05	67	41.7	15.5
92-10-11	73	34.0	19.1
92-10-12	74	32.0	
92-10-13	75	29.5	
92-10-15	77	23.6	
92-10-16	78	24.0	
92-10-18	80	21.8	
92-10-22	84	23.3	
92-10-26	88	32.1	
92-11-01	94	54.0	
92-11-07	100	53.0	
92-11-11	104	58.8	20.1
92-11-15	108	51.0	
92-11-19	112	44.0	
92-11-23	116	51.0	
92-12-02	124	44.0	18.8
92-12-09	131	41.0	19.5
92-12-17	139	29.5	19.8
92-12-23	146	24.0	19.9
93-01-03	156	22.8	20.6
93-01-10	163	14.8	20.5
93-01-17	170	11.5	20.6
93-01-21	174	8.5	20.9
93-01-28	181	7.3	20.7
93-02-03	187	7.0	20.8
93-02-11	195	8.5	20.9
93-02-18	202	6.8	20.7
93-02-25	209	4.5	20.9
93-03-10	222	4.8	20.8
93-03-18	230	1.3	20.9
93-03-30	242	7.0	20.9
93-04-06	249	7.8	
93-04-20	263	9.3	20.9
93-05-11	284	15.0	20.6

Pile L1

Date	Days	Avg Pile Temp ^{0}C	Avg Pile % Oxygen
92-08-02	3	65.0	
92-08-05	6	70.5	
92-08-06	7	69.2	
92-08-10	11	70.0	
92-08-11	12	69.3	

Pile L2

Date	Days	Avg Pile Temp ^{0}C	Avg Pile % Oxygen
92-08-02	3	66.2	
92-08-05	6	68.8	
92-08-06	7	67.3	
92-08-07	8	59.7	
92-08-10	11	67.1	

92-08-12	13	65.5	
92-08-13	14	64.4	
92-08-14	15	67.3	
92-08-15	16	69.8	
92-08-16	17	65.6	15.5
92-08-17	18	66.4	
92-08-20	21	58.4	14.1
92-08-22	23	66.6	15.0
92-08-25	26	64.3	16.1
92-08-27	28	64.6	
92-08-29	30	66.9	
92-08-31	32	64.0	13.0
92-09-05	37	59.8	14.1
92-09-07	39	55.6	
92-09-13	45	61.6	14.5
92-09-17	49	43.5	19.4
92-09-19	51	45.9	
92-09-20	52	42.0	
92-09-23	55	42.0	15.5
92-09-28	60	41.5	17.7
92-10-05	67	34.5	17.8
92-10-11	73	29.0	20.1
92-10-12	74	42.5	
92-10-13	75	28.0	
92-10-15	77	25.0	
92-10-16	78	27.1	
92-10-18	80	25.3	
92-10-22	84	19.8	
92-10-26	88	30.5	
92-11-01	94	52.8	
92-11-04	97	54.2	
92-11-07	100	60.5	
92-11-11	104	54.5	17.3
92-11-15	108	56.0	
92-11-19	112	51.3	
92-11-22	115	46.0	
92-11-23	116	52.5	
92-12-02	124	55.0	18.2
92-12-09	131	54.0	19.0
92-12-17	139	44.0	20.5
92-12-23	146	40.5	20.5
93-01-03	156	38.0	20.7
93-01-10	163	29.5	20.6
93-01-17	170	24.0	20.9
93-01-21	174	22.5	20.8
93-01-28	181	17.3	20.8
93-02-03	187	12.0	20.8
93-02-11	195	5.8	20.7
93-02-18	202	5.5	20.7
93-02-25	209	1.3	20.8
93-03-10	222	2.8	20.8
93-03-18	230	2.0	20.8
93-03-30	242	7.0	20.9

92-08-11	12	69.6	
92-08-12	13	62.8	
92-08-13	14	62.2	
92-08-14	15	62.9	
92-08-15	16	53.5	
92-08-16	17	38.1	15.6
92-08-17	18	53.7	
92-08-20	21	38.1	16.8
92-08-22	23	49.7	15.7
92-08-25	26	42.2	16.8
92-08-27	28	34.9	
92-08-29	30	40.2	
92-08-31	32	59.5	11.1
92-09-05	37	53.8	
92-09-07	39	51.4	
92-09-13	45	53.2	19.9
92-09-17	49	38.0	17.9
92-09-19	51	46.9	
92-09-20	52	34.3	
92-09-23	55	40.1	14.8
92-09-28	60	47.8	16.5
92-10-05	67	41.3	14.1
92-10-11	73	38.7	18.5
92-10-12	74	42.5	
92-10-13	75	41.5	
92-10-14	76	36.9	
92-10-16	78	43.0	
92-10-18	80	45.8	
92-10-22	84	34.3	
92-10-26	88	49.3	
92-11-01	94	64.1	
92-11-04	97	56.5	
92-11-07	100	63.2	
92-11-11	104	64.5	17.7
92-11-15	108	64.5	
92-11-19	112	56.0	
92-11-22	115	49.0	
92-11-23	116	51.5	
92-12-02	124	47.0	16.4
92-12-09	131	45.3	18.0
92-12-17	139	35.5	20.4
92-12-23	146	29.5	20.5
93-01-03	156	22.5	20.5
93-01-10	163	17.8	20.5
93-01-17	170	12.5	20.6
93-01-21	174	12.5	20.7
93-01-28	181	8.3	20.8
93-02-03	187	5.0	20.8
93-02-11	195	3.8	20.8
93-02-18	202	2.5	20.8
93-02-25	209	2.5	20.9
93-03-10	222	4.5	20.7
93-03-18	230	2.5	20.8

93-04-06	249	8.0	
93-04-20	263	9.0	20.8
93-05-11	284	13.0	20.8

93-03-30	242	6.8	20.9
93-04-06	249	7.5	
93-04-20	263	9.0	20.8
93-05-11	284	12.0	20.7

Pile L3

Date	Days	Avg Pile Temp ^{0}C	Avg Pile % Oxygen
92-08-02	2	62.4	
92-08-04	4	66.5	
92-08-05	5	70.2	
92-08-06	6	67.3	
92-08-07	7	67.0	
92-08-10	10	66.8	
92-08-11	11	65.5	
92-08-12	12	62.2	
92-08-13	13	62.1	
92-08-14	14	65.4	
92-08-15	15	69.9	
92-08-16	16	62.6	15.8
92-08-17	17	65.6	16.7
92-08-20	20	64.1	19.6
92-08-22	22	65.1	16.2
92-08-25	25	65.7	
92-08-27	27	63.2	
92-08-29	29	67.1	
92-08-31	31	64.1	15.4
92-09-05	36	64.4	13.1
92-09-07	38	57.0	
92-09-13	44	60.5	14.7
92-09-17	48	53.0	12.6
92-09-19	50	51.5	
92-09-20	51	50.0	
92-09-23	54	36.1	17.2
92-09-28	59	41.2	16.0
92-10-05	66	35.4	15.0
92-10-11	72	37.0	11.7
92-10-12	73	32.0	
92-10-13	74	33.0	
92-10-14	75	29.1	
92-10-16	77	30.3	
92-10-18	79	45.0	
92-10-22	83	37.3	
92-10-26	87	53.7	
92-11-01	96	55.0	
92-11-04	93	70.6	
92-11-07	99	56.4	
92-11-11	103	64.3	20.0
92-11-15	107	55.5	

Pile L4

Date	Days	Avg Pile Temp ^{0}C	Avg Pile % Oxygen
92-08-02	2	60.4	
92-08-05	5	69.0	
92-08-07	7	67.0	
92-08-10	10	66.0	
92-08-11	11	65.5	
92-08-12	12	63.7	
92-08-13	13	63.6	
92-08-14	14	63.8	
92-08-15	15	69.7	
92-08-16	16	66.2	15.0
92-08-17	17	61.5	15.9
92-08-20	20	61.9	19.6
92-08-22	22	61.8	16.0
92-08-25	25	63.4	
92-08-27	27	59.8	
92-08-29	29	60.0	14.3
92-09-05	36	58.8	16.2
92-09-07	38	51.5	
92-09-13	44	56.1	19.6
92-09-17	48	38.5	17.6
92-09-19	50	49.0	
92-09-20	51	31.1	
92-09-23	54	48.0	15.5
92-09-28	59	51.0	18.2
92-10-05	66	49.5	13.3
92-10-11	72	48.0	17.9
92-10-12	73	35.5	
92-10-13	74	41.5	
92-10-14	75	32.7	
92-10-16	77	40.8	
92-10-18	79	43.3	
92-10-22	83	41.3	
92-10-26	87	56.1	
92-11-01	93	61.6	
92-11-04	96	60.9	
92-11-07	99	62.6	
92-11-11	103	61.3	20.1
92-11-15	107	52.0	
92-11-19	111	47.0	
92-11-22	114	43.0	
92-11-23	115	39.0	16.5

92-11-19	111	47.0	
92-11-22	114	49.5	
92-11-23	115	49.5	
92-12-02	123	53.5	20.3
92-12-09	130	52.0	20.2
92-12-17	138	37.0	20.4
92-12-23	144	30.5	20.3
93-01-03	155	28.0	20.4
93-01-10	162	24.5	20.6
93-01-17	169	18.0	20.8
93-01-21	173	8.0	20.7
93-01-28	180	5.5	20.8
93-02-03	186	3.8	20.7
93-02-11	194	5.3	20.8
92-02-18	201	3.5	20.9
92-02-25	208	2.8	20.7
93-03-10	221	6.0	20.7
93-03-18	229	5.0	20.7
93-03-30	241	7.0	20.9
93-04-06	248	8.0	
93-04-20	262	12.0	20.8
93-05-11	283	14.0	20.2

92-12-02	123	46.0	16.1
92-12-09	130	42.0	17.5
92-12-17	138	29.5	17.9
92-12-23	144	19.0	17.0
93-01-03	155	15.5	19.2
93-01-10	162	9.0	20.6
93-01-17	169	5.0	20.8
93-01-21	173	5.0	20.9
93-01-28	180	3.5	20.9
93-02-03	186	2.3	20.9
93-02-11	194	2.5	20.6
92-02-18	201	1.3	20.8
92-02-25	208	2.0	20.8
93-03-10	221	5.0	20.9
93-03-18	229	2.8	20.6
93-03-30	241	7.5	20.9
93-04-06	248	7.3	
93-04-20	262	14.8	20.8
93-05-11	283	16.5	20.2

Pile C1

Date	Days	Avg Pile Temp ^{0}C	Avg Pile % Oxygen
92-08-05	2	64.1	
92-08-07	4	58.7	
92-08-10	7	56.6	
92-08-11	8	55.6	
92-08-12	9	55.6	
92-08-15	12	65.3	
92-08-17	14	56.3	19.9
92-08-20	17	38.1	
92-08-22	19	49.8	
92-08-29	26	62.0	
92-08-31	28	63.0	16.3
92-09-03	31	61.6	8.8
92-09-06	34	69.4	
92-09-13	41	67.9	20.0
92-09-17	45	57.5	16.0
92-09-19	47	57.0	
92-09-20	48	52.8	
92-09-23	52	57.5	11.2
92-09-28	57	57.5	15.8
92-10-05	63	59.0	18.0
92-10-11	69	40.0	18.4
92-10-13	71	39.5	
92-10-16	74	51.5	

Pile C2

Date	Days	Avg Pile Temp ^{0}C	Avg Pile % Oxygen
92-08-05	2	66.0	
92-08-07	4	67.7	
92-08-10	7	66.4	
92-08-11	8	64.8	
92-08-12	9	63.8	
92-08-15	12	68.3	
92-08-17	14	61.3	20.1
92-08-20	17	55.6	
92-08-22	19	54.6	
92-08-29	26	61.0	
92-08-31	28	65.0	
92-09-03	31	61.6	9.1
92-09-06	34	67.8	
92-09-13	41	67.7	19.1
92-09-17	45	53.0	15.9
92-09-19	47	58.5	
92-09-20	48	59.0	
92-09-23	52	53.5	11.3
92-09-28	57	58.5	12.6
92-10-05	63	58.5	13.0
92-10-11	69	50.0	19.3
92-10-13	71	42.5	
92-10-16	74	45.5	

92-10-18	76	54.0		92-10-18	76	65.3	
92-10-22	80	53.0		92-10-22	80	51.0	
92-10-26	87	52.0		92-10-26	87	56.5	
92-11-01	90	57.5		92-11-01	90	58.5	
92-11-04	93	48.8	17.1	92-11-04	93	51.2	17.8
92-11-07	96	50.8		92-11-07	96	53.2	
92-11-11	100	43.9	18.9	92-11-11	100	42.3	18.5
92-11-15	104	43.5		92-11-15	104	45.0	
92-11-19	108	24.0		92-11-19	108	27.5	
92-11-23	112	41.5	20.3	92-11-23	112	40.5	18.1
92-12-02	120	24.0	20.5	92-12-02	120	27.5	20.5
92-12-09	127	20.5	20.4	92-12-09	127	23.5	20.5
92-12-17	135	17.0	20.4	92-12-17	135	20.5	20.6
92-12-23	141	14.0	20.3	92-12-23	141	19.5	20.3
93-01-03	152	10.5	20.5	93-01-03	152	14.5	20.5
93-01-10	159	8.0	20.5	93-01-10	159	9.3	20.5
93-01-17	166	7.0	20.6	93-01-17	166	10.0	20.7
93-01-21	170	5.0	20.9	93-01-21	170	6.5	20.7
93-01-28	177	3.3	20.8	93-01-28	177	3.5	20.8
93-02-03	183	2.5	20.9	93-02-03	183	4.8	20.7
93-02-11	191	3.0	20.8	93-02-11	191	4.5	20.7
92-02-18	198	2.0	20.8	92-02-18	198	2.5	20.9
92-02-25	205	1.8	20.6	92-02-25	205	2.5	20.8
93-03-10	218	6.6	20.9	93-03-10	218	7.0	20.8
93-03-18	226	3.0	20.7	93-03-18	226	3.5	20.7
93-03-30	238	6.0	20.9	93-03-30	238	6.5	20.9
93-04-06	244	13.5		93-04-06	244	11.5	
93-04-20	259	32.5	17.8	93-04-20	259	27.5	17.0
93-05-11	280	31.5	16.4	93-05-11	280	24.5	18.1

D.2 Temperature and Oxygen Plots

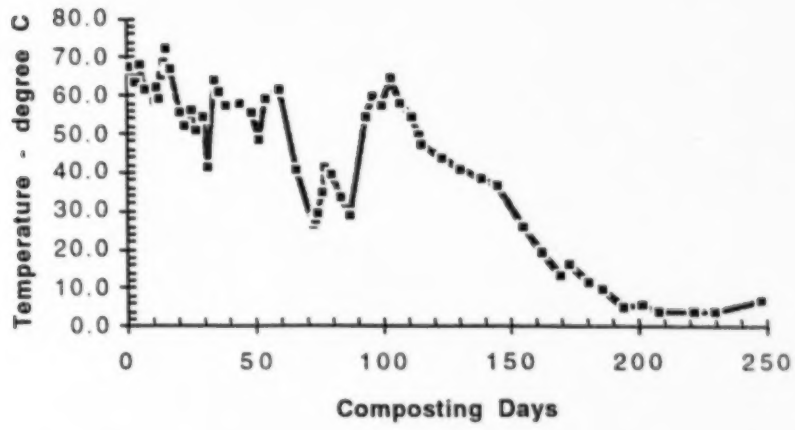


Figure D.1 Pile Temperature vs Composting Days - Pile 1
Med C:N ratio, Low M.C.

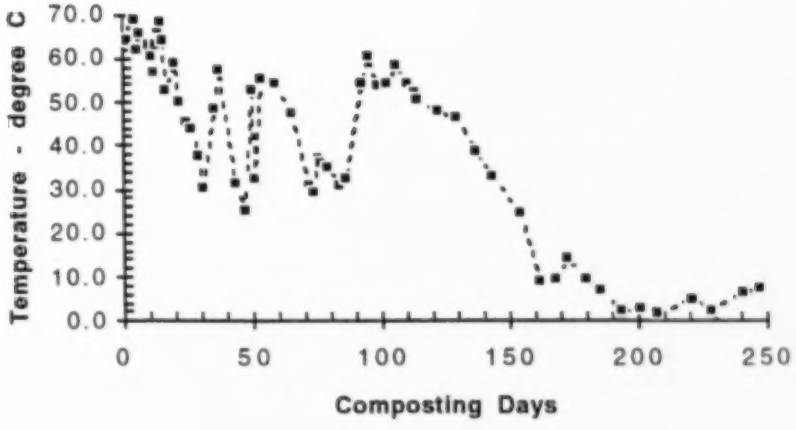


Figure D.2 Pile Temperature vs Composting Days - Pile 2
Hi C:N , Low M.C.

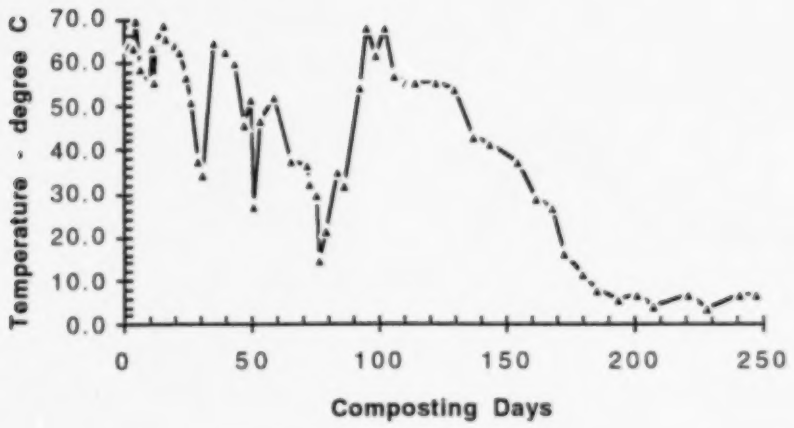


Figure D.3 Pile Temperature vs Composting Days - Pile 3 Med C:N, Hi M.C.

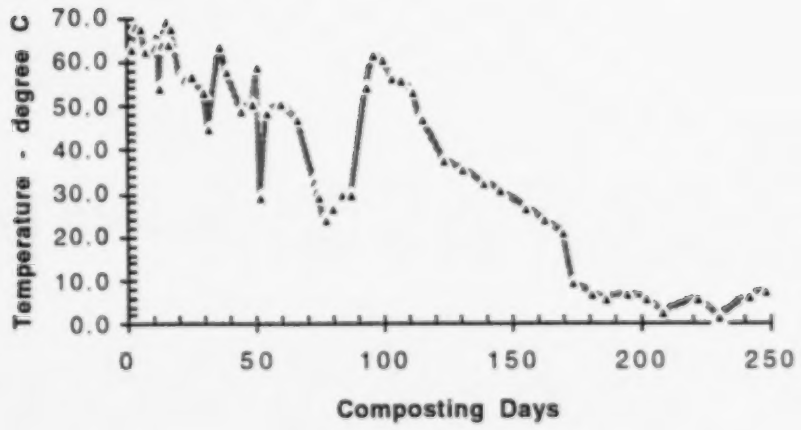


Figure D.4 Pile Temperature vs Composting Days - Pile 4 Hi C:N,Hi M.C.

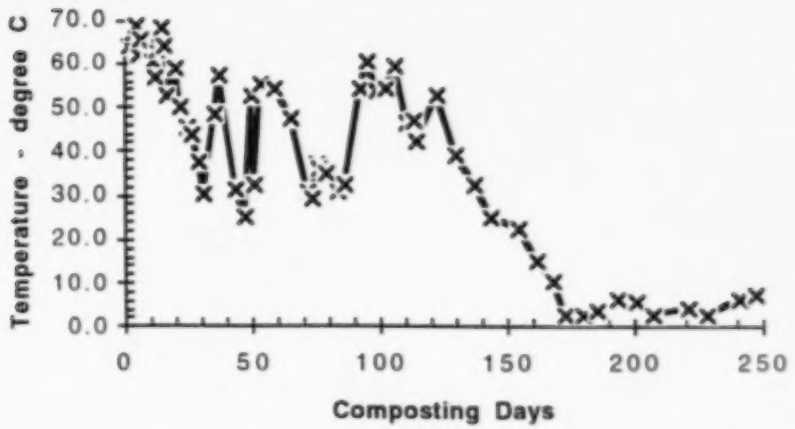


Figure D.5 Pile Temperature vs Composting Days - Pile 5 Med C:N, Hi M.C.

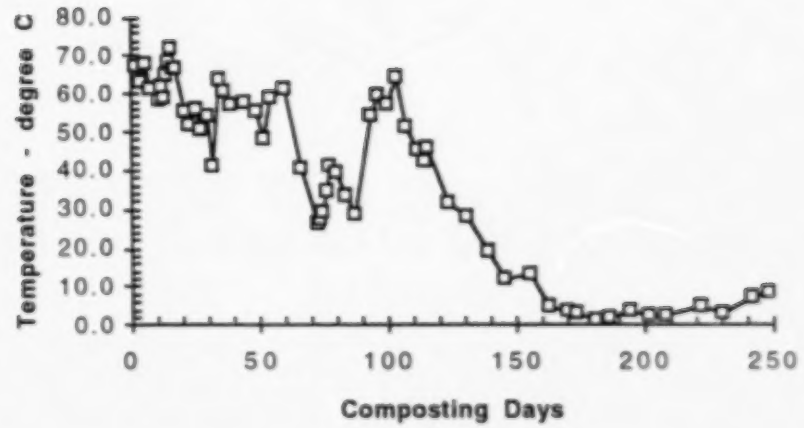


Figure D.6 Pile Temperature vs Composting Days - Pile 6 Hi C:N, Low M.C.

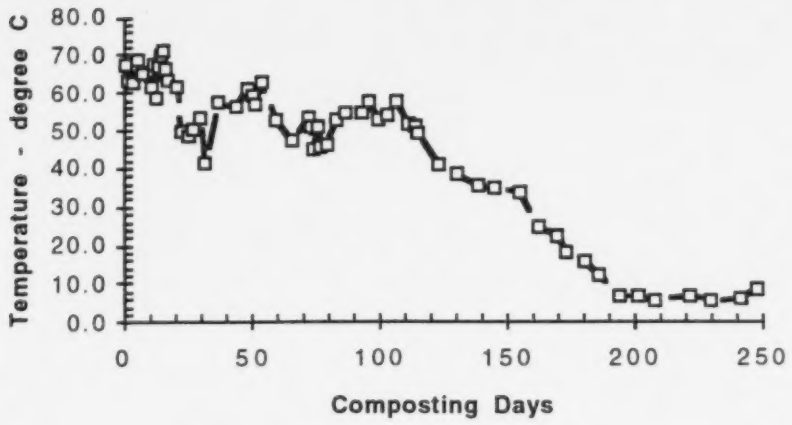


Figure D.7 Pile Temperature vs Composting Days - Pile 7 Med C:N, Hi M.C.

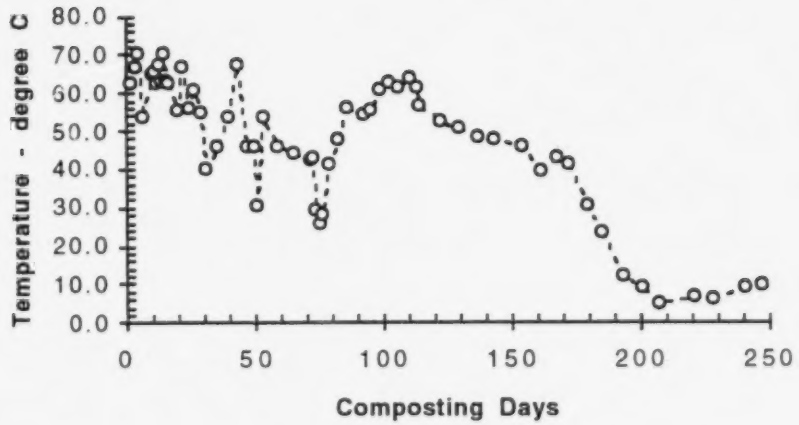


Figure D.8 Pile Temperature vs Composting Days - Pile 8 Hi C:N, Hi M.C.

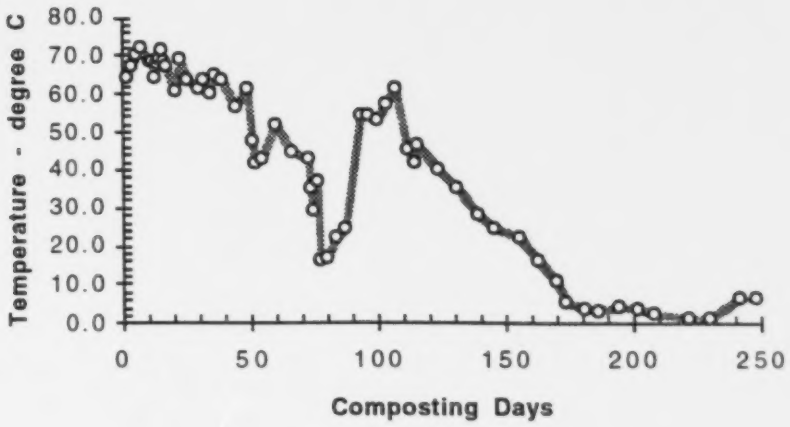


Figure D.9 Pile Temperature vs Composting Days - Pile R1 Med C:N, Hi M.C.

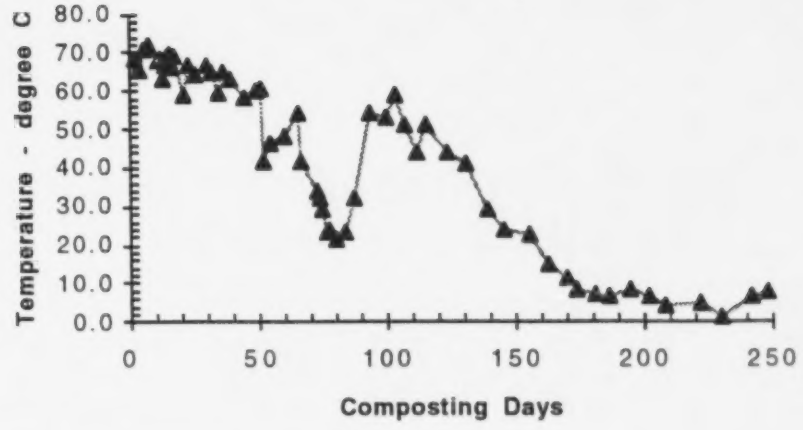


Figure D.10 Pile Temperature vs Composting Days - Pile R2 Med C:N, Hi M.C.

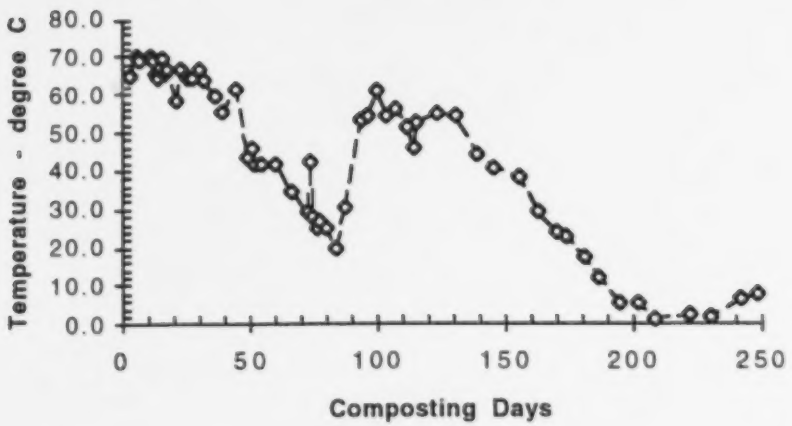


Figure D.11 Pile Temperature vs Composting Days - Pile L1 Low C:N, Hi M.C.

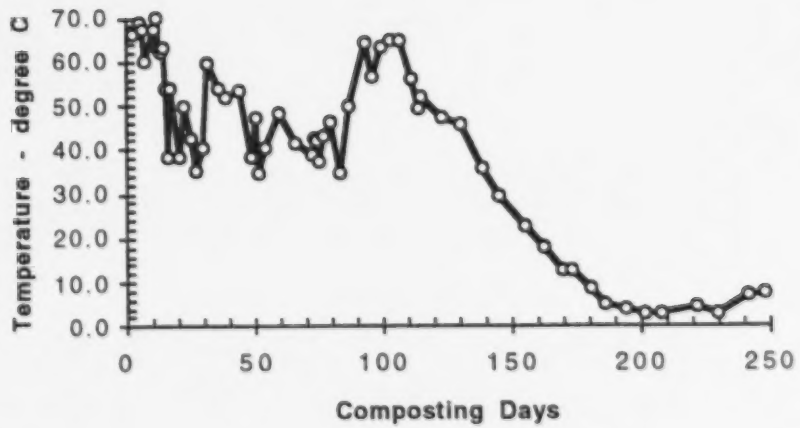


Figure D.12 Pile Temperature vs Composting Days - Pile L2 Low C:N, Low M.C.

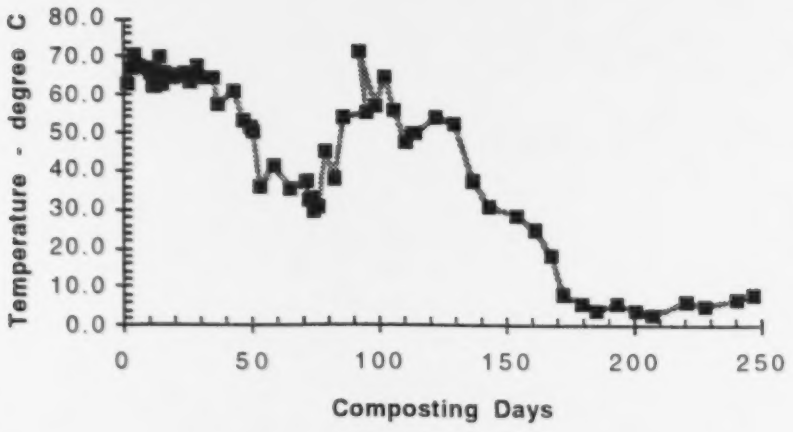


Figure D.13 Pile Temperature vs Composting Days - Pile L3 Low C:N, Hi M.C.

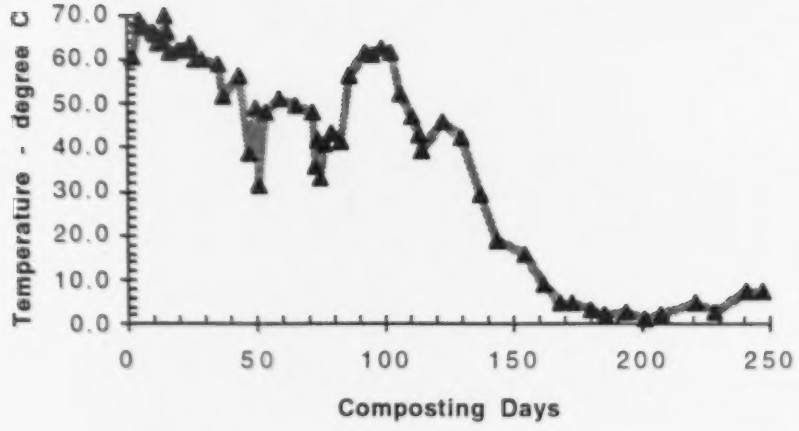


Figure D.14 Pile Temperature vs Composting Days - Pile L4 Low C:N, Low M.C.

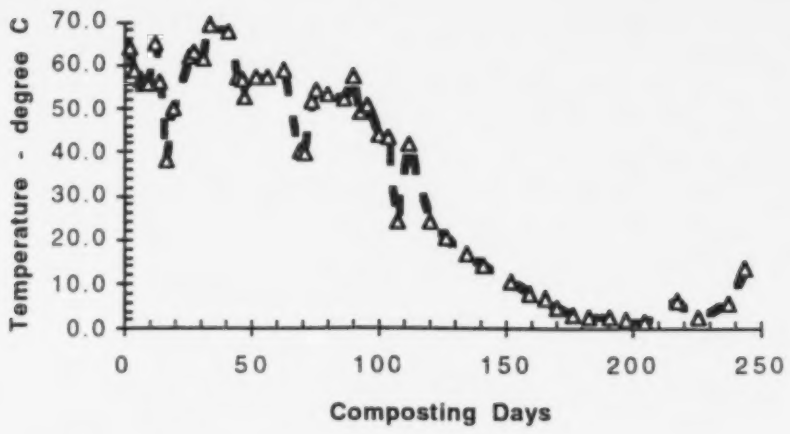


Figure D.15 Pile Temperature vs Composting Days - Pile C1 Control Pile

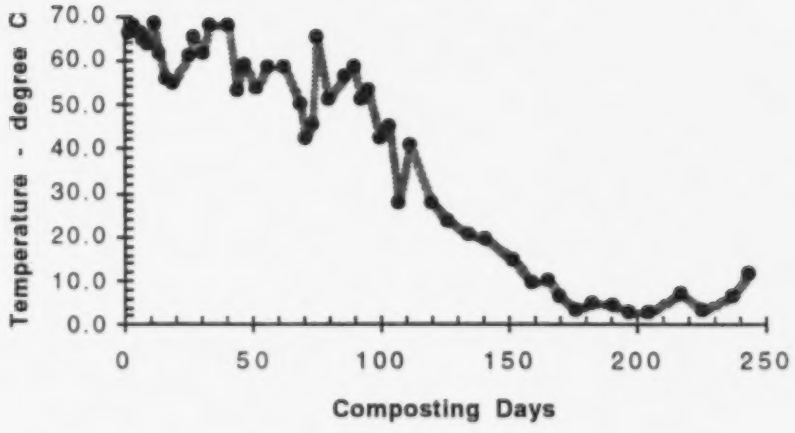


Figure D.16 Pile Temperature vs Composting Days - Pile C1 Control Pile

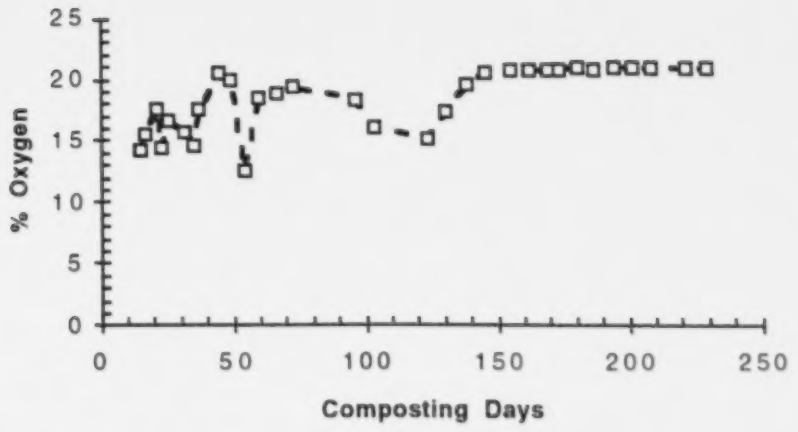


Figure D.17 Pile % Oxygen vs Composting Days - Pile 1
Med C:N, Low M.C.

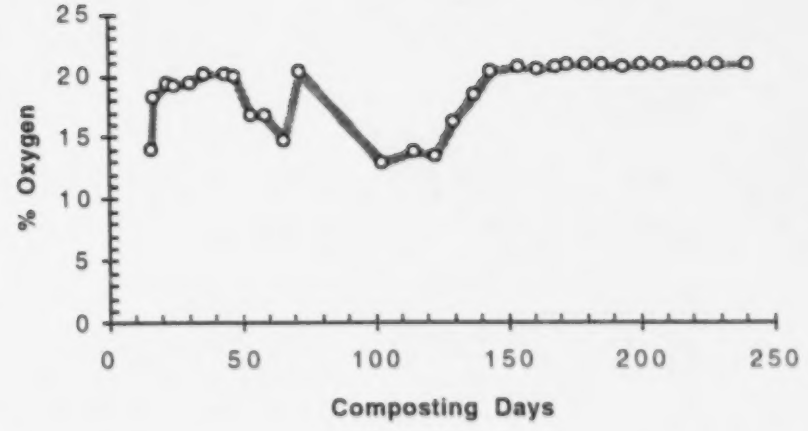


Figure D.18 Pile % Oxygen vs Composting Days - Pile 2
Hi C:N, Low M.C.

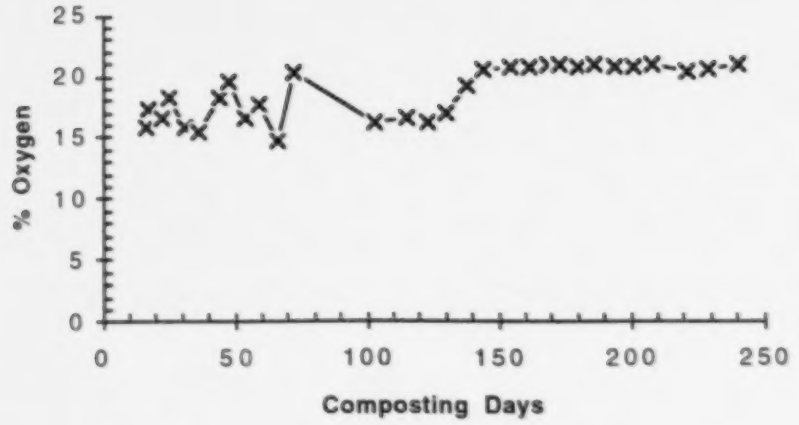


Figure D.19 Pile % Oxygen vs Composting Days - Pile 3 Med C:N, Hi M.C.

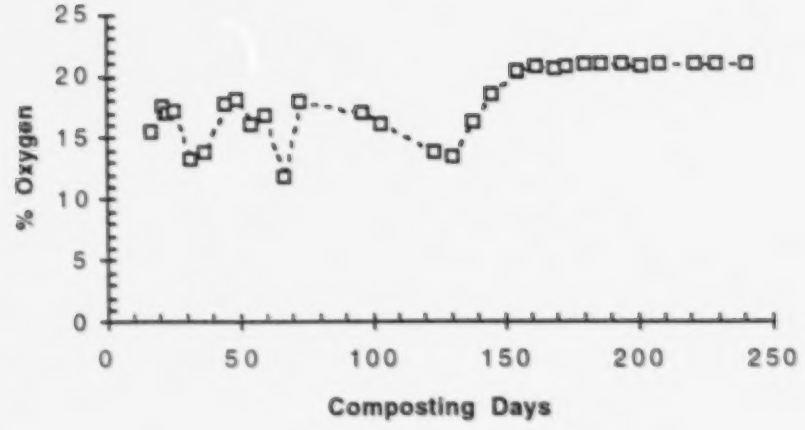


Figure D.20 Pile % Oxygen vs Composting Days - Pile 4 Hi C:N, Hi M.C.

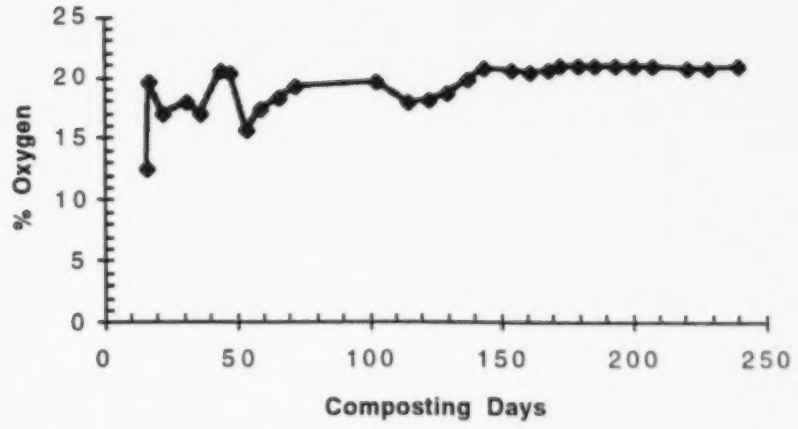


Figure D.21 Pile % Oxygen vs Composting Days - Pile 5
Med C:N, Low M.C.

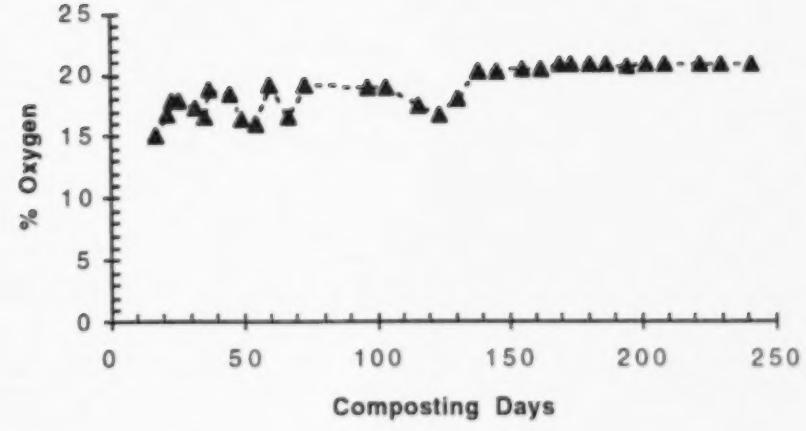


Figure D.22 Pile % Oxygen vs Composting Days - Pile 6
Hi C:N, Low M.C.

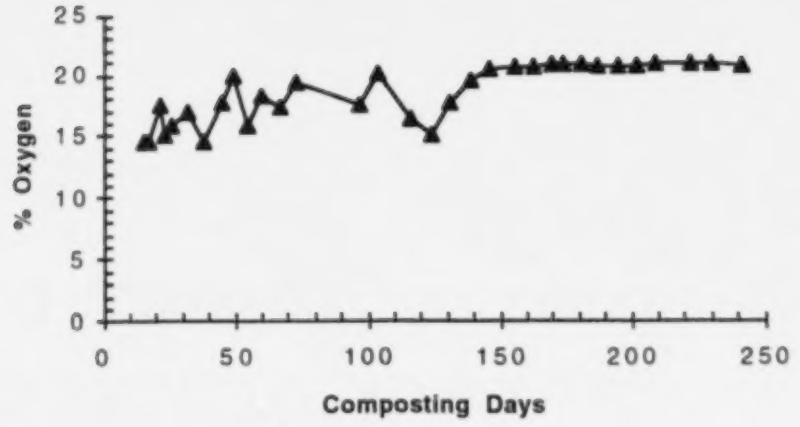


Figure D.23 Pile % Oxygen vs Composting Days - Pile 7
Med C:N, Low M.C.

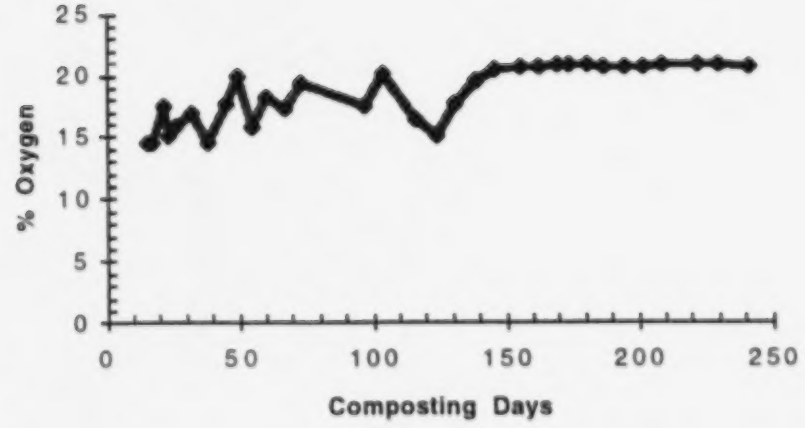


Figure D.24 Pile % Oxygen vs Composting Days - Pile 8
Hi C:N, Hi M.C.

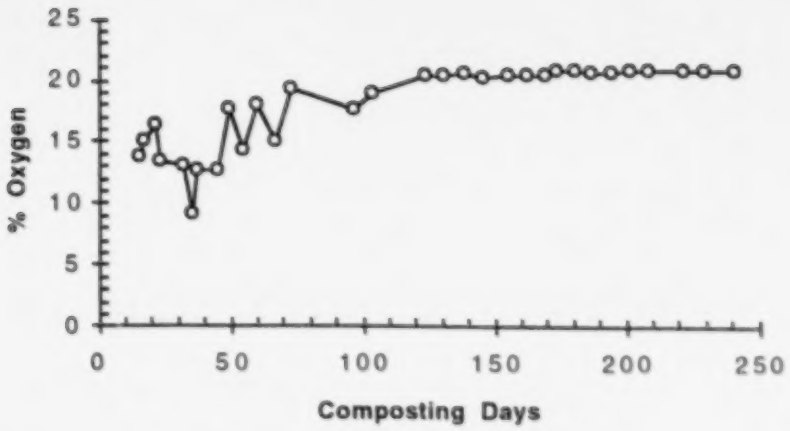


Figure D.25 Pile % Oxygen vs Composting Days - Pile R1 Med C:N, Hi M.C

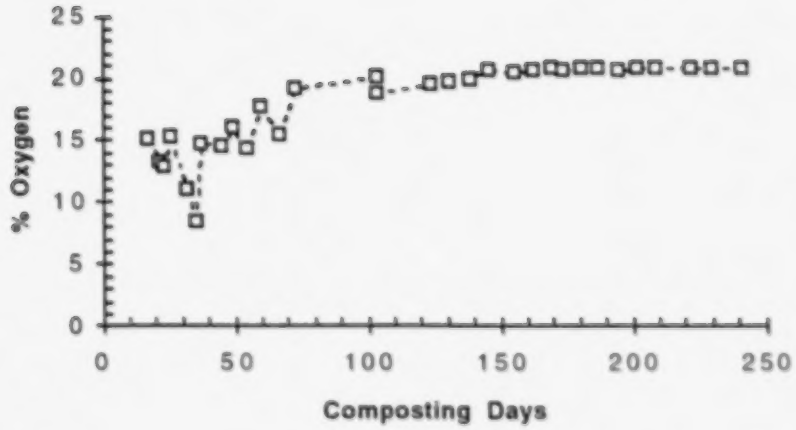


Figure D.26 Pile % Oxygen vs Composting Days - Pile R2 Med C:N, Hi M.C

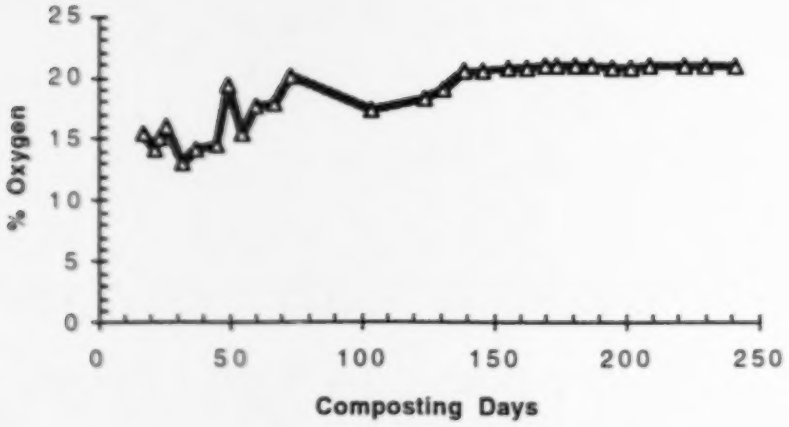


Figure D.27 Pile % Oxygen vs Composting Days - Pile L1 Low C:N, Hi M.C.

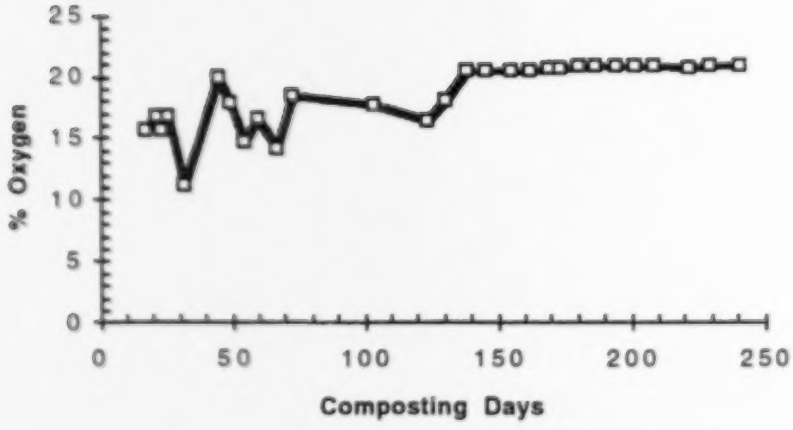


Figure D.28 Pile % Oxygen vs Composting Days - Pile L2 Low C:N, Low M.C.

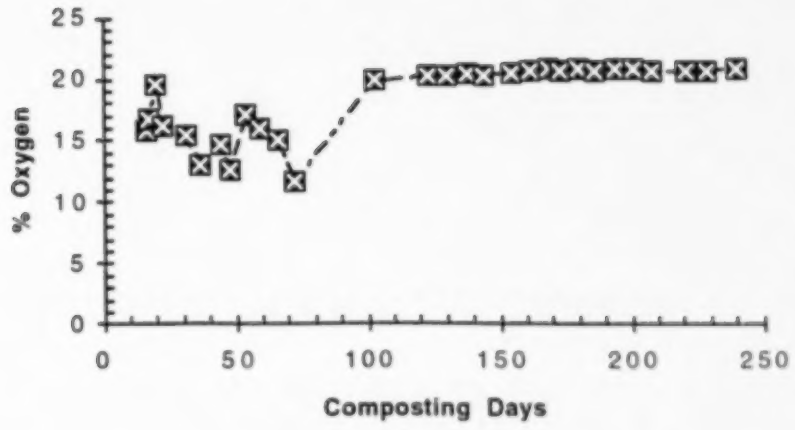


Figure D.29 Pile % Oxygen vs Composting Days - Pile L3 Low C:N, Hi M.C.

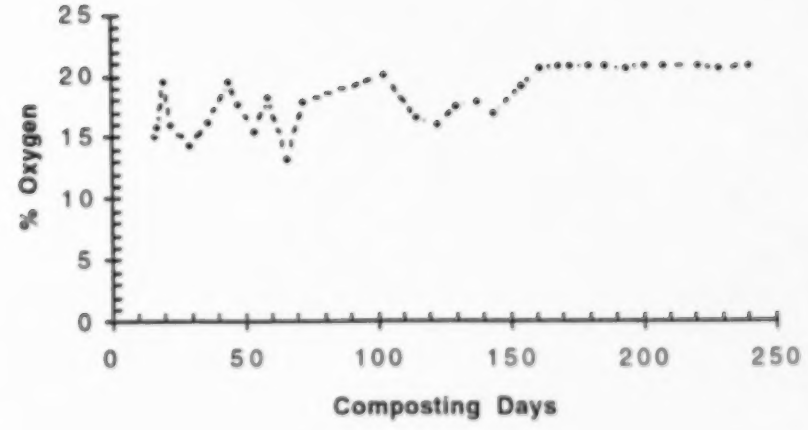


Figure D.30 Pile % Oxygen vs Composting Days - Pile L4 Low C:N, Low M.C.

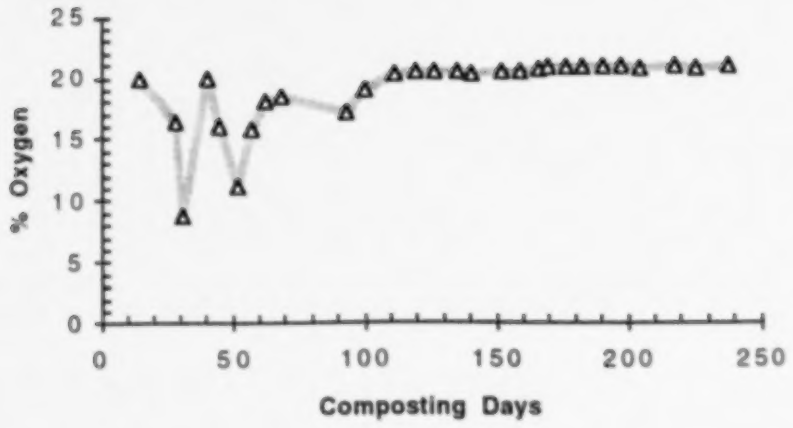


Figure D.31 Pile % Oxygen vs Composting Days - Pile C1 Control Pile

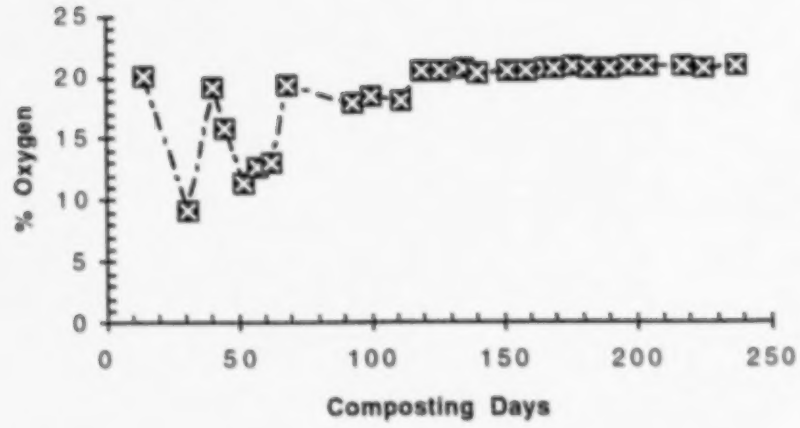


Figure D.32 Pile % Oxygen vs Composting Days - Pile C2 Control Pile

Appendix E - Factorial Results Summary

Table E.1 - Factorial Results Summary

Case 1 Botched Factorial Design Matrix
Full Period Y= % Decrease in TOC (Water extracts)

		Variables							
Pile	**C**	**1**	**2**	**3**	**12**	**13**	**23**	**123**	**Y**
L2	1	-1	-0.89	-1	0.89	1	0.89	-0.89	-82.1
2	1	1	-0.63	-1	-0.63	-1	0.63	0.63	-84.8
L1	1	-1	0.83	-1	-0.83	1	-0.83	0.83	-83.8
4	1	1	0.76	-1	0.76	-1	-0.76	-0.76	-61.3
L4	1	-1	-0.94	1	0.94	-1	-0.94	0.94	-68.0
6	1	1	-0.90	1	-0.90	1	-0.90	-0.90	-68.2
L3	1	-1	0.71	1	-0.71	-1	0.71	-0.71	-73.8
8	1	1	0.64	1	0.64	1	0.64	0.64	-86.0
R1	1	0	0.81	1	0	0	0.81	0	-80.9
R2	1	0	0.73	1	0	0	0.73	0	-80.8
7	1	0	0.77	1	0	0	0.77	0	-78.3
1	1	0	-1.01	-1	0	0	1.01	0	-81.5
3	1	0	0.71	-1	0	0	-0.71	0	-84.5
5	1	0	-0.96	1	0	0	-0.96	0	-80.1

Results

Effects	**Est Value**	**ß**	**(- or +)**	**95% CI**		***Source***	**SS**	**df**	**ms**
0	-156.28	-78.14	3.93	-82.07	-74.21	Total	86232.11	14	6159.44
1	0.99	0.49	5.16	-4.66	5.65	Model	86021.70	8	10752.71
2	-0.27	-0.13	4.87	-5.00	4.73	Residual	210.41	6	35.07
3	3.24	1.62	3.93	-2.31	5.55	Pure Error	6.42	2	3.21
12	4.46	2.23	6.53	-4.30	8.76	Lack of Fit	203.99	4	51.00
13	-8.20	-4.10	5.16	-9.26	1.06	Ftable	19.3	F,4,2, % 5	
23	-9.14	-4.57	4.87	-9.44	0.29	F calc	31.8		
123	-12.16	-6.08	6.53	-12.61	0.45				
						Avg Y	-80.8		
			95 %, 2 sided, df=14-8=6 t=2.45			**replicates**			

Half Normal Plot

i	**Est Effect**	**Abs Value**	**% Pi**
1	2	0.27	7.14
2	1	0.99	21.43
3	3	3.24	35.71
4	12	4.46	50.00
5	13	8.20	64.29
6	23	9.14	78.57
7	123	12.16	92.86

Variable	
1	C:N ratio
2	Moisture Content
3	Porosity Adjustment
C	Constant

Abs value= absolute value of Effects

Case 2 Botched Factorial Design Matrix
Full Period Y= % Increase in Dry Bulk Densities

		Variables							
Pile	**Constant**	**1**	**2**	**3**	**1 2**	**1 3**	**2 3**	**1 2 3**	**Y**
L2	1	- 1	-0.89	- 1	0.89	1	0.89	-0.89	56.9
2	1	1	-0.63	- 1	-0.63	- 1	0.63	0.63	55.8
L1	1	- 1	0.83	- 1	-0.83	1	-0.83	0.83	68.3
4	1	1	0.76	- 1	0.76	- 1	-0.76	-0.76	62.6
L4	1	- 1	-0.94	1	0.94	- 1	-0.94	0.94	59.9
6	1	1	-0.90	1	-0.90	1	-0.90	-0.90	63.4
L3	1	- 1	0.71	1	-0.71	- 1	0.71	-0.71	60.7
8	1	1	0.64	1	0.64	1	0.64	0.64	34.4
R1	1	0	0.81	1	0	0	0.81	0	49.9
R2	1	0	0.73	1	0	0	0.73	0	48.2
7	1	0	0.77	1	0	0	0.77	0	47.6
1	1	0	-1.01	- 1	0	0	1.01	0	49.5
3	1	0	0.71	- 1	0	0	-0.71	0	46.4
5	1	0	-0.96	1	0	0	-0.96	0	71.3

Results

Effects	**Est Value**	**ß**	**(- or +)**	**95% CI**		**Source**	**SS**	**df**	**ms**
0	112.23	56.12	4.89	51.23	61.00	Total	44176.23	14	3155.45
1	-8.82	-4.41	6.41	-10.82	2.00	Model	43851.44	8	5481.43
2	-6.57	-3.28	6.05	-9.33	2.76	Residual	324.79	6	54.13
3	-1.27	-0.64	4.89	-5.52	4.25	Pure Error	2.97	2	1.48
1 2	-10.70	-5.35	8.12	-13.47	2.76	Lack of Fit	321.82	4	80.46
1 3	-5.11	-2.56	6.41	-8.96	3.85	Ftable	19.3	F,4,2, % 5	
2 3	-13.77	-6.88	6.05	-12.93	-0.84	F calc	10.9		
1 2 3	-8.70	-4.35	8.12	-12.47	3.77				
						Avg Y	48.8		
		95 %, 2 sided, df=14-8=6				**replicates**			
		t=2.45							

Half Normal Plot

i	**Effect**	**Abs Value**	**% Pi**
1	3	1.27	7.14
2	13	5.11	21.43
3	2	6.57	35.71
4	123	8.70	50.00
5	1	8.82	64.29
6	12	10.70	78.57
7	23	13.77	92.86

	Variable
1	C:N ratio
2	Moisture Content
3	Porosity Adjustment
C	Constant

Abs value= absolute value of Effects

Case 3 Botched Factorial Design Matrix
Active Period Y= % Decrease in TOC (Water extracts)

		Variables						
Pile	**Constant**	**1**	**2**	**3**	**1 2**	**1 3**	**2 3**	**1 2 3**	**Y**
L2	1	- 1	-0.89	- 1	0.89	1	0.89	-0.89	-80.1
2	1	1	-0.63	- 1	-0.63	- 1	0.63	0.63	-81.2
L1	1	- 1	0.83	- 1	-0.83	1	-0.83	0.83	-76.2
4	1	1	0.76	- 1	0.76	- 1	-0.76	-0.76	-67.6
L4	1	- 1	-0.94	1	0.94	- 1	-0.94	0.94	-53.1
6	1	1	-0.90	1	-0.90	1	-0.90	-0.90	-65.5
L3	1	- 1	0.71	1	-0.71	- 1	0.71	-0.71	-64.8
8	1	1	0.64	1	0.64	1	0.64	0.64	-84.8
R1	1	0	0.81	1	0	0	0.81	0	-76.5
R2	1	0	0.73	1	0	0	0.73	0	-65.0
7	1	0	0.77	1	0	0	0.77	0	-78.3
1	1	0	-1.01	- 1	0	0	1.01	0	-80.2
3	1	0	0.71	- 1	0	0	-0.71	0	-81.4
5	1	0	-0.96	1	0	0	-0.96	0	-76.3

Results

Effects	**Est Value**	**ß**	**(- or +)**	**95% CI**		*Source*	**SS**	**df**	**ms**
0	-147.72	-73.86	5.17	-79.03	-68.69	Total	76973.42	14	5498.10
1	-6.80	-3.40	6.78	-10.18	3.38	Model	76610.01	8	9576.25
2	-1.69	-0.84	6.40	-7.24	5.55	Residual	363.41	6	60.57
3	7.78	3.89	5.17	-1.28	9.06	Pure Error	163.09	2	81.55
1 2	0.92	0.46	8.58	-8.13	9.04	Lack of Fit	200.32	4	50.08
1 3	-10.08	-5.04	6.78	-11.82	1.74	Ftable	19.3	F,4,2, % 5	
2 3	-8.99	-4.50	6.40	-10.89	1.90	F calc	1.2		
1 2 3	-5.80	-2.90	8.58	-11.48	5.69				
						Avg Y	-68.8		
						replicates			

95 %, 2 sided, df=14-8=6
t=2.45

Half Normal Plot

i	Effect	Abs Value	% Pi
1	12	0.92	7.14
2	2	1.69	21.43
3	123	5.80	35.71
4	1	6.80	50.00
5	3	7.78	64.29
6	23	8.99	78.57
7	13	10.08	92.86

Variable	
1	C:N ratio
2	Moisture Content
3	Porosity Adjustment
C	Constant

Abs value= absolute value of Effects

Case 4 Botched Factorial Design Matrix
Active Period Y= % Increase in Dry Bulk Density

		Variables							
Pile	**Constant**	**1**	**2**	**3**	**1 2**	**1 3**	**2 3**	**1 2 3**	**Y**
L2	1	- 1	-0.89	- 1	0.89	1	0.89	-0.89	56.1
2	1	1	-0.63	- 1	-0.63	- 1	0.63	0.63	56.7
L1	1	- 1	0.83	- 1	-0.83	1	-0.83	0.83	63.1
4	1	1	0.76	- 1	0.76	- 1	-0.76	-0.76	59.5
L4	1	- 1	-0.94	1	0.94	- 1	-0.94	0.94	55.4
6	1	1	-0.90	1	-0.90	1	-0.90	-0.90	53.2
L3	1	- 1	0.71	1	-0.71	- 1	0.71	-0.71	53.0
8	1	1	0.64	1	0.64	1	0.64	0.64	30.9
R1	1	0	0.81	1	0	0	0.81	0	45.8
R2	1	0	0.73	1	0	0	0.73	0	39.9
7	1	0	0.77	1	0	0	0.77	0	41.0
1	1	0	-1.01	- 1	0	0	1.01	0	39.6
3	1	0	0.71	- 1	0	0	-0.71	0	46.7
5	1	0	-0.96	1	0	0	-0.96	0	70.3

Results

Effects	**Est Value**	**ß**	**(- or +)**	**95% CI**		*Source*	**SS**	**df**	**ms**
0	103.60	51.80	6.01	45.79	57.81	Total	37608.96	14	2686.35
1	-7.92	-3.96	7.88	-11.84	3.92	Model	37118.15	8	4639.77
2	-6.23	-3.11	7.43	-10.55	4.32	Residual	490.81	6	81.80
3	-3.99	-2.00	6.01	-8.00	4.01	Pure Error	20.09	2	10.04
1 2	-7.02	-3.51	9.98	-13.48	6.47	Lack of Fit	470.72	4	117.68
1 3	-6.02	-3.01	7.88	-10.89	4.87	Ftable	19.3	F,4,2, % 5	
2 3	-15.01	-7.51	7.43	-14.94	-0.07	F calc	23.4		
1 2 3	-6.30	-3.15	9.98	-13.13	6.82				
						Avg Y	41.9		
			95 %, 2 sided, df=14-8=6			**replicates**			
			t=2.45						

Half Normal Plot

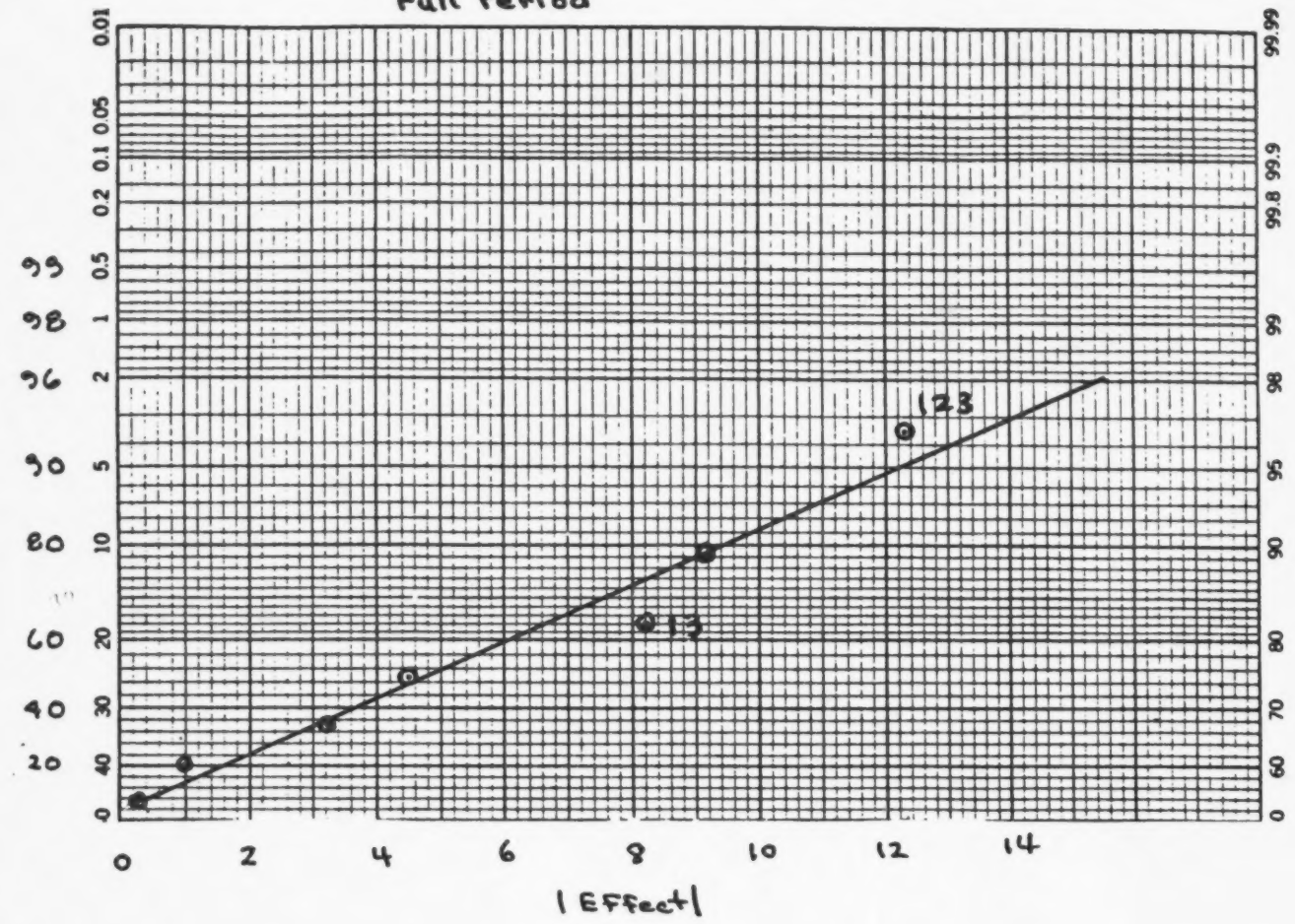
i	**Effect**	**Abs Value**	**% Pi**
1	3	3.99	7.14
2	13	6.02	21.43
3	2	6.23	35.71
4	123	6.30	50.00
5	12	7.02	64.29
6	1	7.92	78.57
7	23	15.01	92.86

Variable	
1	C:N ratio
2	Moisture Content
3	Porosity Adjustment
C	Constant

Abs value= absolute value of Effects

E.1 Half Normal Plot $P_i = (i - 1/2)/n$ $P' = 2P - 100$

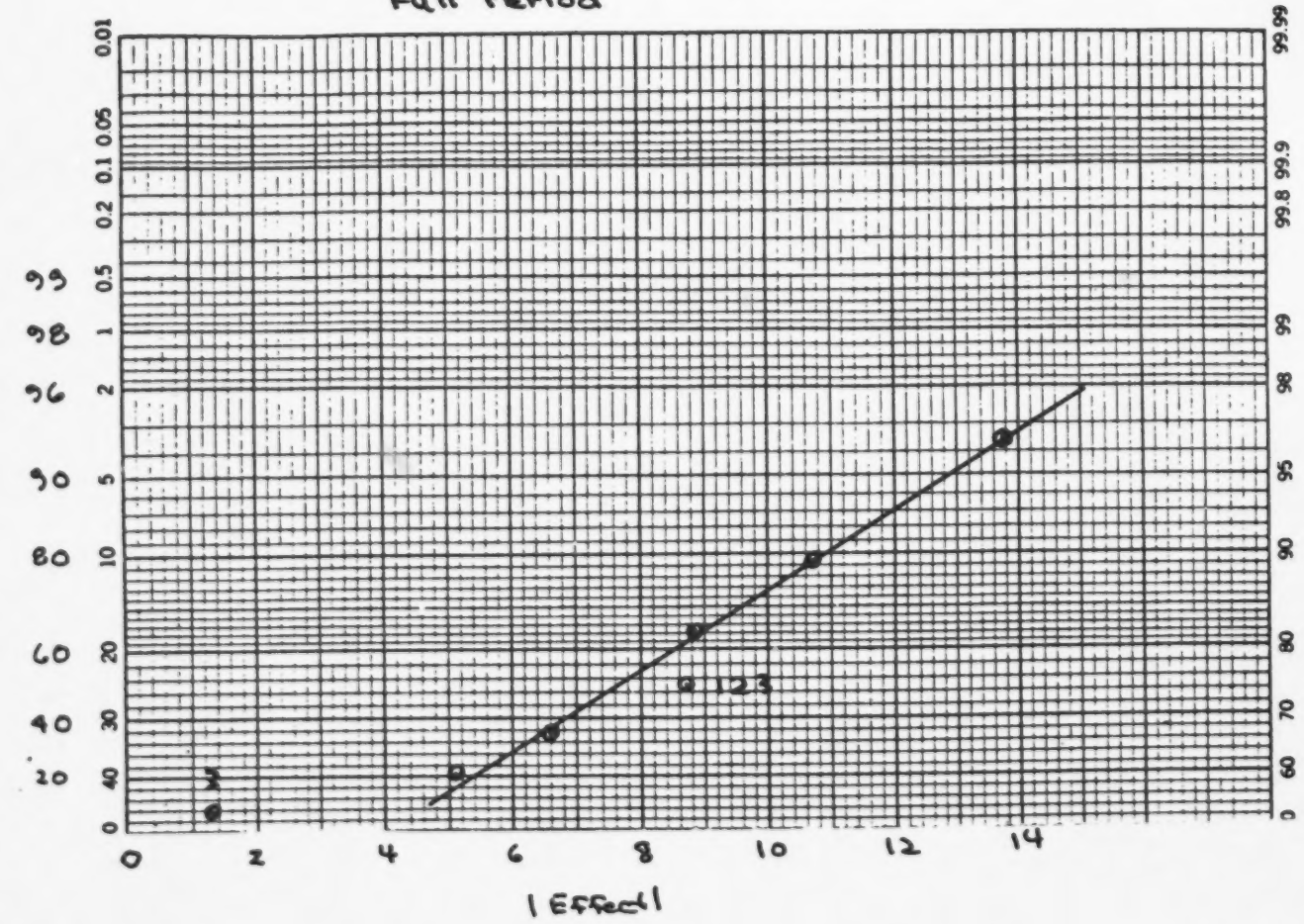
TOC
Full Period



E.2 Half Normal Plot
DBD
Full Period

$P_i = (i - 1/2)/n$

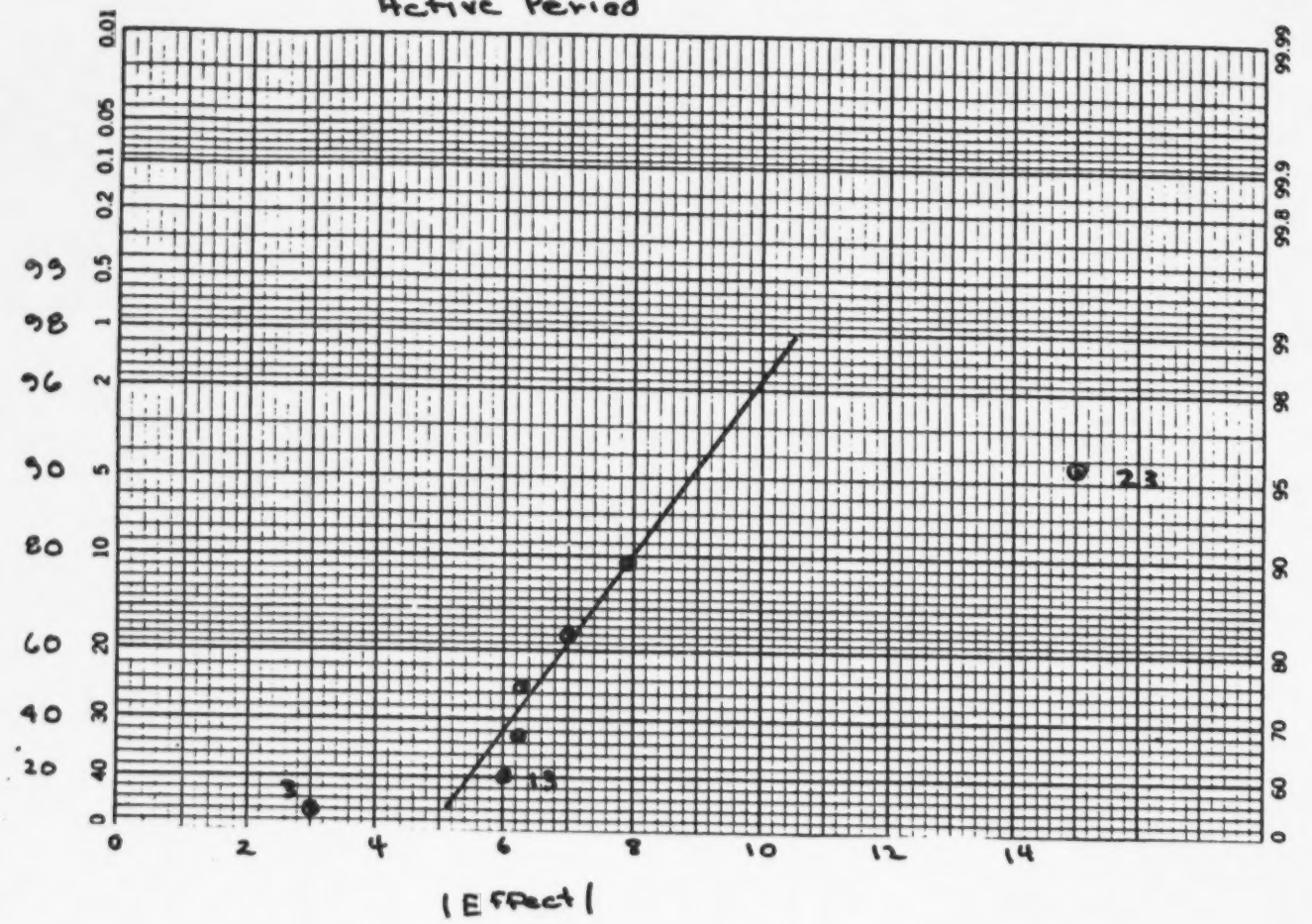
$P' = 2P - 100$



E.4 Half Normal Plot
OBD
Active Period

$P_i = (i - 1/2)/n$

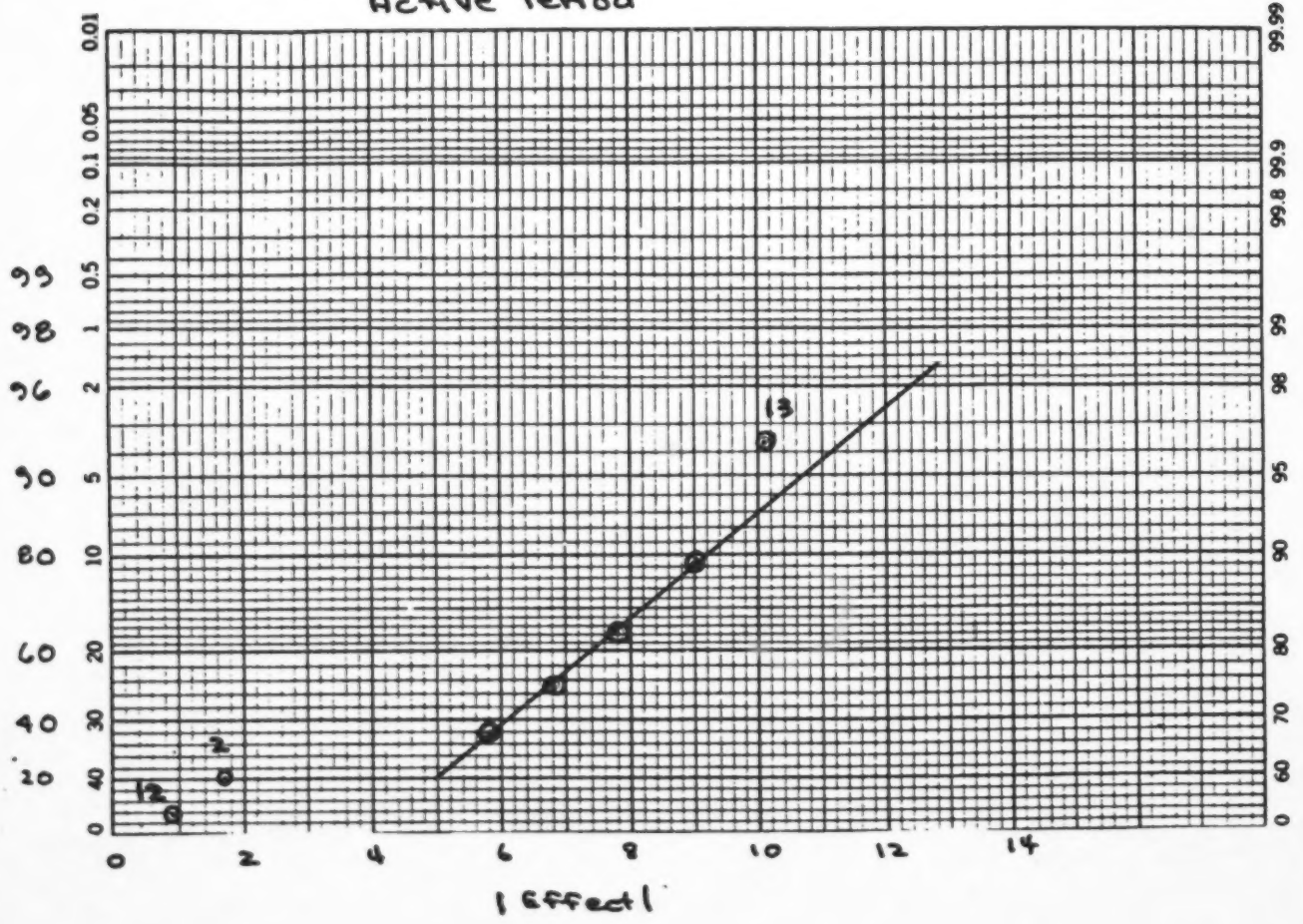
$P' = 2P - 100$



E.3 Half Normal Plot
TOC
Active Period

$P_i = (i - 1/2)/n$

$P' = 2P - 100$



Appendix F - Decomposition Models Summary

Table F.1 - ANOVA Results - Decomposition Models

ANOVA Results - Decomposition Models

% C data		**Model**			
	0 Order	1st Order	2nd Order		
Avg R^2 Value	**0.70**	**0.77**	**0.78**		
Source of variation	sum of squares	degrees of freedom	mean square	F Ratio	F Prob
Between Groups	0.0456	2	0.0228	3.471	0.0423
Within Groups	0.2158	33	0.0065		
Total	0.2614	35			

Reject Ho: that Means are equal

There is no difference between individual group average R^2 squared values using the Student-Newman-Keuls Test with a 5% significance level.

TOC data		**Model**			
	0 Order	1st Order	2nd Order		
Avg R^2 Value	**0.68**	**0.74**	**0.76**		
Source of variation	sum of squares	degrees of freedom	mean square	F Ratio	F Prob
Between Groups	0.0416	2	0.0208	9.0278	0.0007
Within Groups	0.0760	33	0.0023		
Total	0.1176	35			

Reject Ho: that Means are equal

There is a difference between the average R^2 value of the 0 order and 1st order and 0 order and 2nd order using the the Student-Newman-Keuls Test with a 5% significance level.

Table F.2 - Comparison of Pile 1st Order Decomposition Rates

% C data

Reference Pile	Piles Significantly Different than Reference Pile	Significant t value
2	L1	0.04886
5	8	0.04713
8	5	0.04713
	L1	0.01369
	L3	0.04098
	L4	0.04098
L1	2	0.04886
	8	0.01369
	L2	0.01588
L2	L1	0.01588
	L3	0.02174
	L4	0.04723
L3	8	0.01873
	L2	0.02174
L4	8	0.04098
	L2	0.04723

Table F.3 - Comparison of Pile TOC 1st Order Decomposition Rates

TOC data

Reference Pile	Piles Significantly Different than Reference Pile	Significant t value
3	L4	0.02503
7	L4	0.04347
8	L4	0.02927
L4	3	0.02503
	7	0.04347
	8	0.02927